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ARS-106

July 1992

Cotton-Integrated Pest Management: Proceedings of a Symposium

September 3-9, 1990
Alma-Ata, Kazakhstan

Bashkent Uzbekistan.

Richard S. Soper, Nikolai A. Filippov and Sultan N. Alimukhamedov, Editors. 1992. Cotton Integrated Pest Management. Proceedings of a Symposium sponsored by the U.S. Department of Agriculture, Agricultural Research Service, the All-Union Institute of Biological Methods in Plant Protection, and the Middle Asia Institute for Plant Protection. Alma-Ata, Kazakhstan; September 3-9, 1990. U.S. Department of Agriculture, Agricultural Research Service, ARS-xxx, yy pp.

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Edited by:
Richard S. Soper
Nikolai A. Filippov
Sultan N. Alimukhamedov

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Foreword

Richard S. Soper¹

Integrated Pest Management (IPM) has been an important force in shaping crop protection strategies for the past two decades. The evolution of this approach to controlling crop pests has developed without very much attention being paid to the conservation or use of the natural enemy complex. The mass production of insect parasites and predators and their periodic augmentative release has been important in greenhouse culture, especially in the Netherlands, but has not gained much acceptance in the United States. The conservation of natural enemies through cultural practices can be an important method for crop protection. Development of microbial pesticides is also an important method in biological control. These important ecologically benign control techniques have largely been ignored in the current implementation of IPM. The focus has been instead on the conservative use of chemical pesticides. Through a system of scouting to predict damaging pest population levels, IPM technology has been able to dramatically reduce the use of chemical pesticides. This has made a major impact around the world in crop protection. However, recent events in the United States and elsewhere have necessitated a reexamination of the current implementation of IPM. The public concerns for environmental hazards caused by misuse of pesticides, the implication of certain fungicides as carcinogens, the occurrence of some herbicides in groundwater and the hazards to endangered species caused by insecticides, all have caused a dramatic rethinking of how IPM should be conducted. A recent U.S. National Academy of Sciences report urges the scientific community to develop control schemes which use biological control as the first line of defense and apply chemical pesticides as a last resort.

The emphasis on biological control in IPM tactics was found to be of mutual interest between the U.S. Department of Agriculture, Agricultural Research Service and the All-Union Institute of Biological Methods in Plant Protection. As part of a collaborative arrangement on biological control between the U.S. and the former U.S.S.R., it was agreed to co-sponsor a symposium on cotton IPM in which the major thrust would be the maximization of natural enemies. This was hosted in Alma-Ata, Kazakhstan, by the Middle Asia Institute for Plant Protection September 3-9, 1990. This symposium provided a forum for experts in cotton pest management and biological control from both countries. These proceedings are a compilation of papers presented at that symposium.

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Place of Biocontrol in Integrated Pest Management in the former Union of Soviet Socialist Republics

Nikolai A. Filippov¹

At present one of the most important ecological problems for agrarian science and practice is the development and implementation of such techniques of Integrated Pest Management (IPM) of noxious organisms, which, along with prevention of yield losses, would eliminate the harmful influence of chemical pesticides on the environment and provide production of ecologically pure agricultural produce. Under the conditions of intensification of agricultural production in the former U.S.S.R., as well as worldwide, the chemical strategy still predominates in plant protection from pests, diseases and weeds.

Considering the level of current scientific projects and species composition of noxious organisms, it is impossible to completely eliminate chemical control of pests, vectors of diseases and weeds on many crops, especially in cases with fungal epiphytotics, or widespread pest outbreaks. However, public opinion about chemical pesticides has become increasingly negative. It is conditioned by certain concerns about unsatisfactory assortment of pesticides, and the violation of regulations and techniques of their use.

Areas of crops protected by chemical pesticides have been increasing constantly: 36.4 million hectares in 1960, 80.8 million hectares in 1965, 107 million hectares in 1970, 140.3 million hectares in 1975, 167 million hectares in 1985, and 170 million hectares in 1989. To a great extent, this increase has resulted from the implementation of the intensive technologies in which pesticides are often used without due regard for the actual phytosanitary conditions (Novozhilov 1989, Kosenko 1989). The world tendencies are known to be similar -- in recent decades the use of chemical pesticides throughout the world has increased 40 times.

In the former U.S.S.R., more than 300 pesticides are available for application, and more than 100 plant protection chemicals are produced in the country. Up to 250-300 thousand tons of chemical pesticides are applied annually in the former U.S.S.R., which makes up 5.3 percent of the world use. Over 128 million roubles worth of chemical pesticides were imported in 1989 (Melnikov 1989).

Plant protection measures, including application of pesticides, annually prevent losses of 17-20 million tons of

grain, 8 million tons of potatoes, 19 million tons of sugar beets, 1.8 million tons of raw cotton, and 6-6.5 million tons of fruits, vegetables and other agricultural products worth more than 8 billion roubles with an expenditures of 2 billion roubles (Gulenko 1988). Although pesticide application has a good effect economically, it has rather serious negative effects as well. Extensive, and not always scientifically based, use of plant protection chemicals often leads to environmental pollution, violation of sanitary-hygienic standards, and destruction of natural biocenoses. Pesticide applications and their aftereffects cause considerable harm to the beneficial fauna - entomophages, plant pollinators, wild animals and birds. More frequently, resistance development to different pesticide groups in noxious organisms is reported.

Besides searching for new pesticides which are less toxic to mammals and the beneficial fauna, for more extensive use of new cultivation methods, and for disease- and pest-tolerant varieties and hybrids of cultivated plants, we ought to consider biological control employing microbials as an important alternative to chemical control. Considerable attention is being paid to biological control investigations in the former U.S.S.R. More than 1,700 commercial biofactories and biolaboratories in the country deal with the production of biopreparations of about 20 species of entomophages. More than 5,000 persons are working at commercial biolaboratories (Nikonov 1986, 1988). Some factories of the microbiological industry produce biopreparations based on different strains of the entomopathogenic bacterium, *Bacillus thuringiensis* (dendrobacillin, lepidocid, bitoxibacillin, gomelin, etc.). More than 100 scientific and planning institutions in the former U.S.S.R. elaborate different trends in biological control.

In 1989, practical implementation of scientifically-based recommendations resulted in the application of biological methods in the former U.S.S.R. to 27 million hectares, including 19.7 million hectares under entomophages, 7.3 million hectares under micropreparations, and greenhouse area of 18 thousand hectares (single estimate). The share of biological control in the country is about 25 percent of the total volume of pest and disease control (Kosenko 1989).

Insect pheromones are used to monitor the development of pests and to improve pest management over an area of 10 million hectares, including that of cotton (Novozhilov

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1989, Khodzhaev 1990). Biological control of a number of agricultural pests is used in large areas (Table 1). According to the estimate made by the All-Union Institute of Biological Methods in Plant Protection (AUIBMPP), application of biological preparations produces a favorable ecological effect and is economically sound (Table 2).

Some Problems of Integrated Control of Cotton Pests

Cotton is the most important crop in former U.S.S.R. The former U.S.S.R. (alternately with the U.S.A.) is the second or third (after China) largest cotton grower in the world providing one sixth of the total world production. The following are data on cotton production in the former U.S.S.R. (million hectares): 1970 - 2.75; 1980 - 3.15; 1985 - 3.32; 1986 - 3.47; 1987 - 3.53; 1988 - 3.43. Gross yield of raw cotton for 1981-1989 constituted 8.3-8.7 million tons.

Cotton yield capacity did not progress (Tables 6, 7, 8) despite the increase of irrigated areas in cotton-growing republics, use of fertilizers and pesticides (Tables 3, 4, 5), and use of new varieties and technological elements. Big economic and technological mistakes and violations have been made in cotton growing in the former U.S.S.R. Areas under cotton were groundlessly increased and crop rotations were violated. Instead of recommended cotton/alfalfa crop rotations where cotton had to cover no more than 50-55% of total acreage, it became a monoculture in many regions occupying the same fields for dozens of years without breaks. This practice resulted in soil depletion, mass distribution of dangerous weeds, pests and diseases; and decrease in cotton yield and quality. Cotton monopolism in many regions has led to a complex ecological situation and social tension.

The structure of cultivated areas in cotton-growing republics (mainly oriented towards cotton growing) has complicated the phytosanitary situation and does not allow maximum use of climatic conditions or possibilities of irrigation and labor resources to be aimed at increasing the production of fruits, grapes, vegetables, melons, cereals and forage crops. Gross yields and yield capacities of these crops remain low (Tables 9, 10, 11, 12).

In recent decades, cotton protection from noxious organisms became widespread in cotton growing regions, and cotton has received as many as 12 applications of insecticides per growing season. However, this did not reduce pests because of pesticide resistance and destruction of beneficial insects.

Over 210 pests and 30 fungal and bacterial diseases are recorded on cotton in the republics of Middle Asia. More than 200 pest species and 10 disease pathogens are recorded in association with cotton crops (Alimukhamedov 1978, 1983, 1987; Alimukhamedov et al. 1989; Maksumov and Narzikulov 1981; Kovalenkov 1989, 1990). The following pests are of major importance in cotton producing regions of the former U.S.S.R.: Noctuidae, Aphidinae, Thysanoptera, *Tetranychus urticae*, *Bemisia tabaci*, *Hypera postica* (= *Phytonomus variabilis*) *Adelphocoris lineolatus*, *Ostrinia nubilalis* and others (Alimukhamedov 1987, Alimukhamedov et al. 1989, Maksumov and Narzikulov 1981, Kovalenkov 1990, Khamraev 1989).

Scientists in the former Soviet Union have contributed considerably to the development of integrated control of cotton pests, including biocontrol. Economic damage thresholds for different insect pest species and mites have been studied. Many experimental data have been obtained on species composition, ecology and levels of biological effectiveness for entomophage natural populations, production and application technologies for reared entomophages, and commercial microbiopreparations against cotton pests in IPM (Adashkevich et al. 1988, Alimukhamedov et al. 1989, Alimukhamedov et al. 1989, Davletshina 1972, Kovalenkov 1989, Khamraev 1990).

Application of Entomophages Outdoors

Trichogramma

The egg parasitoid, *Trichogramma* spp., is the main agent for biological control of noxious lepidopterans (Lepidoptera). Species included *T. evanescens*, *T. pintoi*, *T. cacoeciae*, *T. semblidis*, *T. embryophagum*. *Trichogramma* is applied by seasonal colonization against noctuid pests such as cabbage moth, *Mamestra brassicae* L., cotton bollworm, *Helicoverpa armigera* Hübner, turnip moth, *Agrotis segetum* Schiff, other species of vegetables, cereals,

sugar beet, cotton, and other crops, as well as against European cornborer *Ostrinia nubilalis* Hübner, and pea moth, *Laspeyresia nigricana* Stephens. The parasitoid is being tested against the codling moth *Laspeyresia pomonella* L. and leaf rollers (Tortricidae) in orchards and vineyards.

At present *Trichogramma* is applied in the former U.S.S.R. on 17 million hectares. More than 750 mechanized production lines are engaged in mass rearing of *Trichogramma* providing the parasitoid to about 50 percent of cotton growing areas. The AUIBMPP and other research institutions in the former U.S.S.R. have developed ways to increase the viability of *Trichogramma* reared on *Sitotroga cerealella*. Research is also being done to select more suitable laboratory hosts for *Trichogramma* and to develop artificial substrates for *Trichogramma* rearing.

Considerable experience on the practical use of *Trichogramma* has been accumulated in different regions of the former U.S.S.R. Scientifically-based and timely application of high-quality parasitoid material in regions favorable for its activity yields 60-80 percent parasitization of noctuid pest eggs and 40-60 percent of eggs of *Ostrinia nubilalis*. Despite certain achievements with *Trichogramma*, its effectiveness is, in some cases, unstable and insufficient. This is mainly caused by neglect of the recommendations for its rearing and application, poor quality of the parasitoid material for releases, and unsuitable weather during its seasonal colonization.

Tests carried out by the AUIBMPP have demonstrated that under optimal conditions the release of the high quality *Trichogramma* provides 80 percent parasitism of pests, lower quality material 60-80 percent, third-class material 35-60 percent, and sub-standard *Trichogramma* less than 35 percent (Golyshin and Greenberg 1989). To increase the effectiveness of *Trichogramma*, recommendations for improving the application techniques have been prepared by the AUIBMPP and other research-institutions. The use of *Trichogramma* results in an additional yield of 2,000-3,000 kg/ha for sugar beet and cabbage and 180-230 kg/ha for corn and winter wheat grain. Application of *Trichogramma* reduces chemical control (2-3 pesticide treatments) and, hence, expenditure on chemical treatments (7-9 roubles per ha).

At present, the release of *Trichogramma* in the field is done mainly by hand which is very laborious. Work is being

done on mechanization of the process. Equipment for ground release of *Trichogramma* by tractors as well as equipment for aerial release have been designed and are being tested.

Mechanized production lines for *Trichogramma* rearing at biofactories have become obsolete and do not meet modern technological and sanitary-hygienic requirements. For this reason research and project-designing institutions are developing mechanized production biofactories (2nd generation) for *Trichogramma* rearing with higher productivity and better sanitary/hygienic conditions which will provide production of high-quality egg parasitoid material.

Bracon

In recent years, *Bracon hebetor* Say has been mass cultured and widely applied to control *Helicoverpa armigera* in the republics of Middle Asia. The parasitoid is reared on either *Ephestia kuehniella* Zeller or *Galleria mellonella* L. in biolaboratories. *Bracon* is released in the field at mass emergence of *H. armigera*. The adults disperse rapidly and parasitize 2nd to 4th instar larvae. The release of 500 to 1,500 individuals per hectare yields 40-50 percent or more parasitism and mortality of *H. armigera* (Adashkevich and Saidova 1988). *Bracon* is released on more than 2 million hectares in the former U.S.S.R. Special equipment for its mass rearing is being developed and tested.

Predaceous bugs

Research institutions of the former U.S.S.R. are developing methods for mass production of the introduced predaceous bugs, *Podisus maculiventris* Say and *Perillus bioculatus* Fabr. for seasonal colonization against *Leptinotarsa decemlineata* Say on early potatoes and eggplants. Field tests, conducted by the AUIBMPP, demonstrated that the predaceous bugs *Perillus* and *Podisus*, released for seasonal colonization, effectively suppress populations of the Colorado potato beetle. Two to three releases of 2nd-3rd instar larvae of *Perillus* (40,000-50,000/ha) and *Podisus* (80,000/ha), depending on the pest population, results in 60-80 percent or higher mortality of egg clusters and larvae of the Colorado potato beetle. From economical and technological view points, seasonal colonization of predaceous bugs is reasonable on early potatoes against 1st-generation egg clusters and larvae of the Colorado potato

beetle and on eggplants against the 2nd-generation of the Colorado potato beetle (Filippov 1989).

Other entomophages

The AUIBMPP and the All-Union Institute of Plant Quarantine (AUIPQ) are carrying out investigations on the effectiveness of the introduced egg parasitoid *Edovum puttleri*, of the Colorado potato beetle. In laboratory tests, parasitism of the Colorado potato beetle eggs in different generations varied from 32-75%, depending on the instar and the quality of the host. *Edovum* parasitizes fresh (1-day) eggs of the Colorado potato beetle more effectively. In field tests three releases of *Edovum* on the plots with eggplants ("parasitoid-host" ratios from 1:3 to 1:7) resulted in 72.5 percent parasitism and destruction of egg clusters. Thus, use of the egg parasitoid against the Colorado potato beetle is promising.

A number of entomophages are also used against pests of citrus and fruit crops in southern parts of the former U.S.S.R. The introduced entomophage, *Aphelinus mali* Haldemann effectively suppresses the reproduction of the woolly apple aphid, *Eriosoma lanigerum* Hausmann, in 100,000 hectares in southern horticultural regions. Releases of the introduced *Rodalia cardinalis* Mulsant provide effective biocontrol of *Icerya purchasi* Maskell on citrus and fruit crops. The parasitoid, *Pseudaphicus malinus* Gahan, is successfully cultured and released against *Pseudococcus comstocki* Kuwana on mulberry and fruit crops. The entomophages, *Cryptolaemus montrouzieri* Mulsant and *Coccophagus gurneyi* Compere, are used to control *Pseudococcus gahani* Green. The introduced predator *Scutellista cyanea* Motschulsky is applied against *Ceroplastes japonicus* Green on citrus and ornamental crops.

The Use of Natural Entomophage Populations

Considerable attention is paid in the former U.S.S.R. to the systematics and ecology of entomophages that are parasites and predators of agricultural crop pests.

Much work has been carried out on studies of taxonomy and ecology of entomophages and the preparation and publication of keys to different groups of parasites and predators of agricultural pests. The institutions engaged in this research include the Institute of Zoology of the Academy of Sciences of the former U.S.S.R., zoological institutes of some republic academies, higher educational institutions, the AUIPP, and the AUIBMPP.

In Middle Europe more than 10,000 phytophagous species are recorded, including 2,620 species of predators and 6,350 species of parasites. The majority of agricultural pests recorded in the former U.S.S.R. are associated with no less than 10-20 entomophagous species. For example, 500 species of natural enemies have been recorded on 50 species of cabbage pests. During the growing season, they suppress 50-60 percent of the population of the cabbage moth, cabbage root fly, whiteflies and aphids. The entomophages of corn bugs, Telenominae, often suppress 60-80 percent of the pest eggs. The aphidophages encountered on winter wheat and maize (coccinellids, syrphids, etc.) can (at certain "predator:host" ratios) eliminate the aphid population completely (Tryapitsin et al. 1982, Voronin 1988).

If insecticides are not applied, entomophagous complexes can considerably reduce the number of pests of field, technical and perennial crops. The process is stimulated by special procedures for conservation and activation of natural populations of entomophages (sowing of nectariferous plants, sowing of grass, and creation of entomological reservations). Chemicals are not needed when 250-300 entomophages are encountered per 100 plants. Over 190 species of parasites and predators of insect pests and mites occur in the cotton agroecosystem (Narzikulov and Kovalenkov 1985). Of special importance is the regulating role of such entomophages as Carabidae, Staphylinidae, Coccinellidae, Chrysopidae, Syrphidae, Ichneumonidae, Braconidae, Chalcididae, Aphidiidae, Tachinidae and Aphelinidae. The use of natural populations of predators and parasitoids of agricultural pests is one of the most important trends in biological control in the former U.S.S.R. and annually allows elimination of chemical treatments in the area of 10-11 million hectares.

Microbiological Pest Control

A number of biopreparations based on different strains of the entomopathogenic bacterium *Bacillus thuringiensis* Berliner have been developed and produced by the microbiological industry in the former U.S.S.R. (Stroeve and Juschenko 1986, Kandibin 1989). Recommendations have been developed on the use of bacterial preparations against a number of cotton pests (Agzamova et al. 1988). At present the following biopreparations are manufactured:

- **Entobacterin** - dry powder, titre not less than 30 billion spores/g, biological activity not less than 100 Au/g.
- **Dendrobacillin** - dry powder, titre not less than 100 billion spores/g, biological activity 3,000 Au/g (concentrated) and wettable powder, titre 60 billion spores/g, biological activity 2,000 Au/g.
- **Bitoxibacillin** - dry powder, titre not less than 45 billion spores/g, 0.6-0.8 percent of exotoxin content, biological activity not less than 1,500 Au/g.
- **Gomelin** - dry powder, titre not less than 90 billion spores/g, biological activity not less than 2,700 Au/g.
- **Lepidocid** - dry powder, concentrated titre not less than 100 billion spores/g, biological activity not less than 3,000 Au/g.

The list of insect pests susceptible to *Bacillus thuringiensis* includes about 150 lepidopterous species. Bacterial insecticidal preparations are more specific than chemical ones, are relatively safe for humans, animals and plants, do not induce resistance in insects, have no negative effect on the beneficial entomofauna, and are widely used against Pieridae, Yponomeutidae, Tortricidae, Pyralidae, Geometridae, Noctuidae, Lasiocampidae and Orgyidae.

Biopreparations based on *Bacillus thuringiensis* are applied against the above-mentioned pests as aqueous suspensions at rates of 1-5 kg per hectare. Two to three treatments of cabbage, fruit crops, berries, grapes, sugar beet, alfalfa, cotton, etc. are 70-90 percent effective. Bitoxibacillin, recommended against various lepidopterous species, is highly effective against larvae of the Colorado potato beetle. Three treatments (2-3 kg/ha/treatment) result in 92-97 percent reductions of pest numbers which is equally effective as chemical insecticides. Commercial bacterial entomopathogenic preparations are applied in the former U.S.S.R. in an area of about 2 million hectares. Studies have been carried out on the use of entomopathogenic fungi against a number of agricultural pests in greenhouses and

outdoors. For example, biopreparation Boverin (a mixture of spores and products of the vital activity of the fungus *Beauveria bassiana* Bals.) has been recommended against the Colorado potato beetle. The preparation is produced in biolaboratories with a titre of 2-6 billion spores/g. It is applied at the time of mass emergence of Colorado potato beetle larvae at the rate of 2 kg/ha, with a sublethal dose of chlorophos (0.4 kg/ha). Investigations are in progress on a biopreparation of the fungus *Entomophthora* for controlling aphids.

Intensive studies are being made on entomopathogenic viruses which can be applied against insect pests. The following viral preparations are being tested or have been recommended for use in the former U.S.S.R.:

- **Virin-EKS** - titre not less than 1 billion polyhedra/ml. It is recommended against small larvae of *Mamestra brassicae* on cabbage, pea and beet at the rate of 0.10-0.15 kg/ha.
- **Virin-GYAP** - titre not less than 3 billion granules/ml. It is recommended against *Laspeyresia pomonella* at the beginning and peak of larval emergence at the rate of 0.3 kg/ha.
- **Virin-KSH** - titre not less than 1 billion polyhedra/ml. It is being tested against 1st and 3rd instars of *Malacosoma neustria* larvae on fruit crops and forest trees at the rate of 0.2 kg/ha.
- **Virin-OS** - titre not less than 3 billion granules/g. It is being tested on cotton and other crops against 1st and 2nd instars of *Scotia segetum* at the rate of 0.3 kg/ha.
- **Virin-HS** - titre not less than 7 billion polyhedra/g. It is being tested on cotton against 1st and 2nd instars of *Helicoverpa armigera* at the rate of 0.3 kg/ha.
- **Virin-ENSH** - titre not less than 1 billion polyhedra/ml. It is recommended on fruit and forest trees during *Lymantria dispar* reproduction, at a density of 0.5-2 egg clusters/tree and at the rate of 2 ml/egg cluster.
- **Virin-ABB** - titre 3 billion polyhedra and granules/ml. It is recommended in orchards and forests on mulberry against *Hyphantria cunea* Drury at the rate of 0.1 kg/ha.

Methods are under development for mass rearing of phytophagous insects necessary for the production of viral preparations. Techniques for commercial production of high-quality preparations are being improved.

The bacterial preparation of Isachenko bacterium *Salmonella enteridis* developed by All-Union Institute of Agricultural Microbiology has been recommended for microbiological control of rodents. It is mixed with grain having a titre of not less than 1 billion spores/g and it is produced as an aminobonal preparation with a titre of not less than 0.1 billion spores/g. The grain bacterodencid is applied without bait, while the aminobonal preparation is mixed with bait (boiled grain, potatoes, etc.) before use. The mice, *Mus musculus* L. and *Apodemus silvaticus* L., and the vole *Microtus agrestis* L. are most susceptible to bacterodencid. The preparation is applied in the field at the rate of 1-2 kg/ha and in storehouses at the rate of 100 g/100 m². The biological effectiveness of bacterodencid is 75-80 percent, greatly depending on the quality of the preparation and is produced in biolaboratories.

Conclusion

The assortment of biological preparations for plant protection from agricultural pests allows considerable reduction in the use of chemical insecticides. It is possible to use biocontrol to reduce chemical treatments on vegetables and potatoes by 50-60 percent outdoors and by 35-40 percent in horticulture. At present, it is extremely urgent to replace chemical pesticides with biological, cultural and selection methods in the regions of dietetic food and child food production, at resorts, water-preservation zones, agricultural regions around industrial centers and other zones of great ecological danger.

To increase the scale of application of biological control of agricultural pests, it is necessary to carry out further investigations, especially in the following urgent trends:

- Increase in the number of biological methods for suppression of outdoor pests such as Coleoptera, Aphidinae, Diptera, Acridodea.
- Improvement of techniques of production and application of biological control of agricultural pests, including development of up-to-date technical equipment for biological control, and new types of industrial biolaboratories.
- Development of methods of activation of natural populations of entomophages and entomopathogens.
- Expansion of international cooperation in the introduction of the beneficial organisms.

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Table 1. Areas of biocontrol of main pests in the former U.S.S.R.

Pest species	Volume of work in 1989 (1,000 ha)		
	Total	Included means	
		Chemical	Biological
Rodents - <i>Apodemus</i> <i>Meriones</i> <i>Microtus</i> sp.	11,772.4	7,500.6	4,271.8
<i>Pyrausta sticticalis</i> D.	7,437.3	5,329.4	2,107.9
<i>Agrotis</i> sp.	4,604.8	132.6	4,472.2
<i>Mamestra</i> , <i>Spodoptera</i> sp., etc.	4,140.4	175.1	3,965.3
<i>Ostrinia nubilalis</i> Hb.	1,967.9	17.8	1,950.1
<i>Helicoverpa armigera</i> Hb.	5,421.5	453.0	4,968.5
<i>Leptinotarsa decemlineata</i> Say	6,492.1	6,187.0	305.1
Vegetable pests	2,088.6	1,285.1	803.5
Fruit pests	4,319.8	3,699.0	620.8
Grape pests	1,972.7	1,830.3	142.4
Pests of cotton complex	8,992.1	2,687.0	6,305.1

Table 2. Economic effectiveness of application of biocontrol in the former U.S.S.R. in 1970-1988¹

No.	Indices	1970	1975	1980	1985	1986	1987	1988
1.	Volume of biomeans application million hectares including, entomophages biopreparations	4.1	10.7	17.0	22.6	24.4	24.1	26.7
		3.9	7.6	11.9	16.8	17.6	18.3	19.2
		0.2	3.1	5.1	5.8	6.8	5.8	7.5
2.	Value of extra (preserved) produce, million roubles	144.0	396.0	596.0	825.0	880.0	875.0	970.0
3.	Expenditures on application of biological means, including costs on harvesting and sale of extra produce, million roubles	84.0	235.0	345.0	488.0	510.0	513.0	569.0
4.	Conditional net profit, million roubles	60.0	161.0	251.0	337.0	360.0	362.0	401.0

¹ Data obtained by the lab of economics of AUIBMPP

Table 3. The area of irrigated lands in the former U.S.S.R. republics growing cotton (1,000 hectares)

Republics	1970	1980	1985	1986	1987	1988
Former U.S.S.R.	11,100	17,487	19,951	20,487	20,485	20,782
Uzbekistan	2,696	3,476	3,930	4,020	4,109	4,149
Kazakhstan	1,451	1,961	2,172	2,231	2,318	2,260
Azerbaijan	1,108	1,195	1,318	1,330	1,345	1,370
Kyrgyzstan	883	955	1,009	1,020	1,028	1,037
Tajikistan	518	617	653	662	675	686
Turkmenistan	643	927	1,107	1,185	1,224	1,258

"Narodnoje khozjaistvo SSSR b 1983 godu." Annual Statistics, Moscow, 1989.

Table 4. Supplies of mineral fertilizers to the former U.S.S.R. agriculture (per 100% of nutritional substances)

	1970	1980	1985	1986	1987	1988
	1,000 tons					
All mineral fertilizers	10,317	18,763	25,395	26,514	27,412	27,196
including:						
nitric	4,605	8,262	10,950	11,475	11,787	11,587
phosphorous	3,133	5,590	7,615	8,354	8,564	8,556
potash	2,574	4,904	6,822	6,677	7,052	7,044
	kg/l ha of arable land					
All mineral fertilizers	46.8	83.9	113.2	118.1	122.1	122.4
including:						
nitric	20.9	36.9	48.8	51.1	52.5	52.7
phosphorous	14.2	25.0	34.0	37.2	38.2	38.2
potash	11.7	21.9	30.4	29.8	31.4	31.5

"Narodnoje khozjaistvo SSSR in 1988 godu." Annual Statistics, Moscow, 1989.

Table 5. Supplies of Plant Protection chemicals to the former U.S.S.R. agriculture (in 100% according--to a.i.) in 1,000 tons

	1970	1980	1985	1986	1987	1988
All plant protection chemicals	170	279	362	346	333	308
Including herbicides	50	127	160	172	169	148

"Narodnoje khozjaistvo SSSR in 1988 godu." Annual Statistics, Moscow, 1989.

Table 6. Gross yield of raw cotton in the former U.S.S.R. republics (1,000 tons)

Republics	Average per year					
	1971 -1975	1976 -1980	1981 -1985	1986	1987	1988
Former U.S.S.R.	7,667	8,547	8,314	8,234	8,084	8,689
Uzbekistan	4,895	5,359	5,159	4,989	4,858	5,365
Kazakhstan	305	317	302	333	312	325
Azerbaijan	441	627	707	784	697	616
Kyrgyzstan	205	208	87	68	73	79
Tajikistan	810	906	917	922	872	963
Turkmenistan	1,011	1,130	1,142	1,138	1,272	1,341
Including fine fibre cotton						
Former U.S.S.R.	656.7	794.0	1,087.7	1,187.6	1,182.8	1,333.5
Uzbekistan	204.6	301.0	494.5	583.7	534.2	561.0
Tajikistan	257.0	267.6	289.2	308.7	276.4	328.9
Turkmenistan	194.1	225.4	304.0	295.2	372.2	448.6

"Narodnoje khozyaistvo SSSR v 1988 godu." Annual Statistics, Moscow, 1989.

Table 7. Cotton yield in the republics of the former U.S.S.R. (centners/ha)

Republics	Average per year					
	1971 -1971	1976 -1976	1981 -1985	1986	1987	1988
Raw cotton						
Former U.S.S.R.	27.3	28.1	25.6	23.7	22.9	25.3
Uzbekistan	28.5	29.4	26.7	24.3	23.1	26.6
Kazakhstan	26.6	27.0	23.3	25.9	24.4	25.4
Azerbaijan	21.6	27.2	23.9	26.1	23.0	20.6
Kyrgyzstan	27.6	28.3	19.1	23.5	23.5	24.7
Tajikistan	30.7	30.7	29.8	29.5	26.9	30.1
Turkmenistan	23.1	22.4	21.4	17.5	20.1	21.1
Fine fibre cotton						
Former U.S.S.R.	23.1	22.7	24.6	23.9	24.2	24.6
Uzbekistan	27.6	28.0	30.2	28.8	26.9	27.6
Tajikistan	31.5	30.7	29.7	31.5	30.3	31.3
Turkmenistan	15.2	14.5	16.9	15.0	18.8	18.9

"Narodnoje khozyaistvo SSSR v 1988 godu." Annual Statistics, Moscow, 1989.

Table 8. Gross yield of raw cotton (fibre) in the former U.S.S.R. republics (1,000 tons)

Republics	Average per year					
	1971 -1975	1976 -1980	1981 -1985	1986	1987	1988
Former U.S.S.R.	2,474	2,612	2,453	2,660	2,502	2,748
Uzbekistan	1,580	1,620	1,509	1,622	1,505	1,719
Kazakhstan	103	97	93	108	96	101
Azerbaijan	147	203	212	262	225	203
Kyrgyzstan	68	65	26	21	20	24
Tajikistan	262	289	278	293	276	299
Turkmenistan	314	338	335	354	380	402

Raw cotton yield (fibre) in the former U.S.S.R. republics (centners/ha)

Former U.S.S.R.	8.8	8.6	7.6	7.7	7.1	8.0
Uzbekistan	9.2	8.9	7.8	7.9	7.1	8.5
Kazakhstan	8.9	8.3	7.2	8.4	7.5	7.9
Azerbaijan	7.2	8.8	7.2	8.4	7.4	6.8
Kyrgyzstan	9.2	8.9	5.8	7.0	6.5	7.5
Tajikistan	9.9	9.8	9.0	9.4	8.5	9.3
Turkmenistan	7.2	6.7	6.3	5.4	6.0	6.3

"Narodnoje khozyaistvo SSSR v 1988 godu." Annual Statistics, Moscow, 1989.

Table 9. Agricultural crop areas in cotton growing republics of the former U.S.S.R. in 1988 (1,000 ha)

Republics	Total land under cultivation	Cereals	Technical crops including cotton	Including Vegetable and melon crops	Forage crops
Former U.S.S.R.	211,500	114,912	14,497	8,501	73,640
Uzbekistan	4,349	1,049	2,057	235	1,008
Kazakhstan	35,658	24,290	481	327	10,560
Azerbaijan	1,468	539	321	73	535
Kyrgyzstan	1,314	552	63	51	648
Tajikistan	848	241	331	48	228
Turkmenistan	1,243	198	637	75	333

"Narodnoje khozyaistvo SSSR v 1988 godu." Annual Statistics, Moscow, 1989.

Table 10. Agricultural crop yield in cotton-growing republics of the former U.S.S.R. in 1988 (centners/ha)

Republics	Cereals	Potatoes	Vegetables
Former U.S.S.R.	17.0	103	157
Uzbekistan	20.9	99	209
Kazakhstan	9.3	112	169
Azerbaijan	26.3	70	202
Kyrgyzstan	31.9	146	201
Tajikistan	15.6	163	209
Turkmenistan	22.0	100	124

"Narodnoje khozyaistvo SSSR v 1988 godu." Annual Statistics, Moscow, 1989.

Table 11. The area under fruit and berry crops and vineyards in cotton-growing republics of the former U.S.S.R. in 1988 (1,000 hectares)

Republics	Fruits and berries		Grapes	
	Total	Including fruit-bearing	Total	Including fruit-bearing
Former U.S.S.R.	2,848	2,218	1,105	884
Uzbekistan	212	136	128	92
Kazakhstan	98	72	26	18
Azerbaijan	135	96	195	169
Kyrgyzstan	47	34	9	6
Tajikistan	71	51	33	25
Turkmenistan	26	15	28	21

"Narodnoje khozyaistvo SSSR v 1988 godu." Annual Statistics, Moscow, 1989.

Table 12. Gross yield and yielding capacity of fruit and berry crops and grapes in cotton - growing republics of the former U.S.S.R. in 1988

Republics	Fruits and berries		Grapes	
	Gross yield (1,000 tons)	Yielding capacity (centners/ha)	Gross yield (1,000 tons)	Yielding capacity (centners/ha)
Former U.S.S.R.	8,909	39.8	5,581	61.8
Uzbekistan	623	45.6	655	70.8
Kazakhstan	275	37.9	94	49.9
Azerbaijan	427	44.3	1,250	73.7
Kyrgyzstan	145	42.3	28	44.6
Tajikistan	212	41.4	178	71.8
Turkmenistan	50	34.2	165	80.8

"Narodnoje khozyaistvo SSSR v 1988 godu." Annual Statistics, Moscow, 1989.

Table 13. Areas of biocontrol means application in the former U.S.S.R. in 1970-1989 (single estimate)

Year	Outdoors (million ha)			Greenhouse (1,000 ha) Total entomophages and microbiopreparations
	Total	Entomophages	Microbiopreparations	
1970	4.1	3.9	0.25	0.05
1975	10.7	7.6	3.1	1.0
1980	17.0	11.9	5.1	4.2
1985	22.6	16.7	5.9	10.4
1986	24.4	17.6	6.8	11.5
1987	24.1	18.4	5.7	13.7
1988	26.4	19.3	7.4	14.3
1989	27.2	19.7	7.5	18.0

Table 14. Application areas of different biocontrol means in greenhouses in the former U.S.S.R. in 1989 (single estimate)

Biocontrol means	Area - 1,000 ha
Entomophages	
<i>Phytoseiulus persimilis</i>	6,160
<i>Encarsia formosa</i>	1,857
<i>Aphidoletes aphidimyza</i>	348
<i>Aphidius matricariae</i>	146
<i>Amblyseius mckenziei</i>	399
<i>Chrysopa carnea</i>	21
<i>Macrolophus costalis</i>	7
<i>Micromus angulatus</i>	14
<i>Cycloneda limbifer</i>	37
Microbiopreparations	
<i>Trichoderma lignorum</i>	5,401
<i>Verticillium lecanii</i>	1,293
<i>Salmonella enteritidis</i>	711
Bitoxibacillin, <i>B. thuringiensis</i>	916
<i>Beauveria bassiana</i>	140
<i>Ampelomyces</i> sp.	184
<i>Aschersonia</i> sp.	31
Risoplan	49
Total	18,000

Table 15. Application areas of different biocontrol means outdoors in the former U.S.S.R. in 1989

Bicontrol means	Area - 1,000 ha
Entomophages	
<i>Trichogramma</i> sp.	17,124.6
<i>Bracon hebetor</i>	1,974.8
<i>Chrysopa carnea</i>	446.3
<i>Phytomyza orobanchia</i>	124.5
<i>Metaseiulus</i> sp.	15.2
<i>Cryptolaemus</i> sp.	7.6
<i>Encarsia partenopea</i>	5.1
<i>Scutellista cyanea</i>	0.11
<i>Telenomus</i> sp.	0.5
Total	19,685.7
Microbiopreparations	
<i>Salmonella enteritidis</i>	5,299.7
<i>Bacillus thuringiensis</i>	0.0
Bitoxibacillin BT	819.0
Dendrobacillin BT	837.5
Lepidocide BT	758.3
Gomelin BT	35.0
<i>Trichoderma lignorum</i>	3.1
<i>Ampelomyces</i> sp.	0.5
Fitolavin	2.75
BVK - lizin	9.3
Total	7,778.8

Table 16. Volumes of biocontrol application on agricultural crops (former U.S.S.R., 1985-2005, 1,000 ha)

Crops	1985		1990		1995		2000		2005	
	BC ¹ means total	Incl. MBP ²	BC means total	Incl. MBP	BC means total	Incl. MBP	BC means total	Incl. MBP	BC means total	Incl. MBP
Cereal and leguminous	4,427.9	1,626.8	6,500	3,195	7,000	3,387	7,300	3,66	7,600	3,800
including:										
corn	1,795.3	57.4	2,100	820	2,200	840	2,250	865	2,300	880
etc.	1,564.6	1,554.7	2,000	1,075	2,200	1,140	2,350	1,295	2,300	1,340
legumes	925.4	14.7	2,400	1,300	2,600	1,400	2,700	1,500	3,000	1,580
Technical	8,755.5	640.9	9,900	4,220	11,000	4,256	11,250	4,400	11,500	4,500
including:										
cotton	4,375.3	481.6	5,000	2,420	5,600	2,826	5,700	3,130	5,750	3,200
sugar beet	4,004.6	154.5	4,550	1,000	4,800	855	4,880	940	4,950	950
sunflower	343.3	4.8	350	20	600	175	670	225	800	350
Vegetables and melons	1,510.3	743.8	2,300	780	4,200	2,275	7,000	4,900	7,500	5,000
including:										
potatoes	260.5	245.1	500	260	900	600	3,600	3,000	3,650	3,040
vegetables	1,232.8	498.7	1,750	520	3,210	1,665	3,600	1,880	3,600	1,920
melons	17.0		50		90	10	100	20	250	40
Forage crops	2,603.8	1,328.9	2,900	1,450	3,200	1,600	3,650	1,720	4,000	1,750
including:										
perennial grasses	2,595.2	1,327.8	2,850	1,440	3,100	1,500	3,400	1,500	3,800	1,670
Perennial plants	919.6	762.3	1,200	810	1,500	910	1,400	1,000	1,600	1,100
including:										
orchards	798.1	643.2	990	670	1,150	760	1,180	810	1,620	860
vineyards	120.1	119.1	210	140	350	150	220	190	280	240
Total	22,597.9	5,885.7	27,500	10,500	30,100	12,500	32,500	15,850	35,000	16,500

¹ Biocontrol

² Microbiopreparations

Cotton Insect Problems in the United States -- An Overview

D. D. Hardee¹

Abstract

Eighteen major and eleven minor insects in 1989 caused an estimated loss of more than \$686 million to cotton production in the United States. The relative importance of each of the insects is elaborated with reference to which geographical area the total damage is done. Among several items listed, current challenges in cotton insect management include continuing increases in insecticide resistance, cost of registration and re-registration, etc.

Introduction

In 1987, cotton (*Gossypium* spp.) was grown in 90 countries on 32.6 million hectares which produced 48.4 million tons of seed cotton with an average yield of 1,485 kg seed cotton per ha (Green and Lyon 1989). Seventy-five percent of the area grown in cotton was in developing countries, but they accounted for only 62% of total production; the major producers in order were China, U.S.A., the former U.S.S.R., Pakistan, and India. Cotton has been one of the major agricultural crops grown in the United States since the late 1700s (Handy 1896) and currently ranks as the fourth most valuable crop in the U.S. after corn, soybeans, and wheat. A total of 3.86 million ha of cotton was harvested in 1989 with an average yield of 542 kg lint per ha or a total of 12.1 million bales (218 kg/bale). Texas, California, and Mississippi were the three leading states in production and accounted for almost 60% of the total crop (King et al. 1990). The estimated value of the 1989 crop (from 15 states in the south and west) was near \$4 billion for lint alone, with an additional \$507 million for cottonseed (Anonymous 1990).

Cotton is a plant seemingly designed especially for insects, since Young (1969) lists 13 major and 13 minor insects which attack cotton in the U.S. In a previous review of the evolution of cotton insect management systems in the U.S., Ridgway and Lloyd (1983) noted that insects were reported to cause extensive damage to cotton as early as the 1800s. Since that time, depending on changes in production systems that resulted from introduction of new pests and improved equipment, insect damage to cotton has changed many times. Perhaps the greatest change

resulted from the extension of the range of the boll weevil, *Anthonomus grandis grandis* Boheman, from Mexico in 1892 (Howard 1894). This insect had spread eastward from Texas to North Carolina by 1926 leaving devastation and poverty in its path. Since 1950, two major events shaped future cotton insect control. These were (1) development of resistance by the boll weevil to chlorinated hydrocarbon insecticides and the resulting development of organophosphates as their replacement, and (2) emergence of the tobacco budworm, *Heliothis virescens* (F.), as a major pest of cotton. A third event of importance was the acceptance in the late 1970s through the present of pyrethroids as the insecticides of choice for budworms and bollworms, *Helicoverpa zea* (Boddie).

Arthropod pests reduced yield of the 1989 cotton crop by 9.2% (Head 1990). This amounted to a loss of 1.1 million bales or \$319.7 million in revenue. Furthermore, the average cost for controlling arthropod pests was \$93.49/ha across the U.S. Cotton Belt. Thus, the estimated total costs due to arthropod pests, that is reduced yield plus cost of treatment, was \$686.1 million.

In this report, I will first present the current status and economic importance of each major pest that occurs in cotton from planting to harvest. Next, I will describe the minor insect problems (that must be dealt with) and their potential for becoming major problems. Finally, I will relate to you the current challenges that we face in cotton insect management in the U.S.

Major Insect Problems

Major insect pests are presented in the order in which they attack cotton (from seedling stage to harvest).

Cutworms (Various species; Lepidoptera: Noctuidae)

Cutworms damage cotton in the seedling stage by cutting stems completely at the soil surface and occasionally feeding on the leaves. Several species of cutworms, including the variegated cutworm, *Peridroma saucia* (Hübner), may develop in weeds or other crops, especially legumes, and subsequently attack cotton planted on land previously in weeds or legumes (Young 1969). Cotton planted in wet, grassy areas or growing in an area receiving

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excessive rainfall may have to be replanted due to feeding by cutworms resulting in stand reduction. Cutworms are considered minor pests in some areas, and no reliable cost estimates are available.

Seedling Thrips

Onion thrips, *Thrips tabaci* Lindeman; Tobacco thrips, *Frankliniella fusca* (Hinds) (Thysanoptera: Thripidae). Adult and nymphal thrips attack cotyledons and new leaves of the cotton plant by piercing leaf tissues with their sharp mouthparts and sucking the juices (Head and Williams 1983). This feeding damage can substantially reduce cotton stand and necessitate occasional replanting. Excessive feeding may cause "possum-eared," stunted cotton which may ultimately yield less and delay maturity by as much as 2-3 weeks.

Mirids

Cotton fleahopper, *Pseudatomoscelis seriatus* (Reuter) Plant bugs, *Lygus lineolaris* (Palisot de Beauvois); *Lygus hesperus* Knight (Heteroptera: Miridae). The entire cotton plant may be injured during feeding by mirids which remove plant sap and inject insect enzymes into the plant. Feeding may occur at all stages of growth of the plant, but most damage occurs from the 4th leaf stage to bloom, during which time leaves become deformed and ragged, pinhead squares turn brownish black and are shed (blasted squares), and developing pollen is destroyed. Feeding on mainstem terminals can produce abnormal branching ("crazy cotton") and delayed fruiting in the cotton plant. *Lygus hesperus* is prominent in the western U.S. (Leigh et al. 1988), *P. seriatus* is the predominant species in Texas (Sterling et al. 1988), and *L. lineolaris* primarily fills the niche in the rest of the Cotton Belt (Scott et al. 1986).

Boll Weevil

Anthonomus grandis grandis Boheman (Coleoptera: Curculionidae). Uncontrolled populations of the boll weevil can effectively cause 100% damage in a cotton field, which accounts for its status as the number one insect problem in the U.S. (Cross 1973). As seen in Table 1, the boll weevil was the leading pest of cotton in 1989. Adults

may cause minor damage by feeding on seedlings and tender foliage, but the main concern is oviposition in squares (flower buds) or bolls, followed by larval development inside fruiting forms with subsequent abscission of squares and lint damage in bolls.

As of this writing, parts of the U.S. are involved in a boll weevil eradication program financed jointly by the producers and the USDA Animal and Plant Health Inspection Service (APHIS). The boll weevil essentially has been eliminated from Virginia, North Carolina, and part of South Carolina, and these states are currently part of a containment program. Current APHIS-coordinated boll weevil cooperative programs include the Southeast Boll Weevil Eradication Program (approximately 500,000 acres of cotton in Florida, Georgia, South Carolina, and southern Alabama), the West Texas Containment Program (270,000 acres of cotton in the High and Rolling Plains of West Texas), and the Southwest Boll Weevil Eradication Program (including approximately 300,000 acres of cotton in western Arizona, southern California and northwestern Mexico) (Anonymous 1989). Utilizing insecticides and pheromone traps, and through a series of grower referenda and expanding technologies and successes, the long-range plan is to free the U.S. entirely of boll weevils over the next 10-15 years by forcing it back into Mexico, followed by a containment barrier across northern Mexico.

Bollworms/Budworms

Bollworm, *Helicoverpa zea* (Boddie); Tobacco budworm, *Heliothis virescens* (Fabricius) (Lepidoptera: Noctuidae). The bollworm and the budworm together are the "bollworms" attacking cotton. Larvae hatch and feed wherever eggs are laid, and they may destroy terminals, buds, and young squares, as well as eat significant portions of older squares and bolls to the extent that fruiting forms are destroyed (Head 1981). The bollworm occurs throughout the Cotton Belt, whereas the budworm is primarily a pest of cotton from Texas eastward. The budworm is more difficult to kill than the bollworm, and resistance to organophosphate and pyrethroid insecticides is more common in the budworm.

Resistance management is currently being recommended (Luttrell and Roush 1987) and used to help curb increasing occurrences of resistance to pyrethroid insecticides. This program consists of (1) use of non-pyrethroid insecticides

from planting until bloom; (2) where needed, selective use of pyrethroids for a 6-week period after bloom; and (3) use of non-pyrethroids thereafter in late season. Data for 1989 (Table 1) show that the bollworm/budworm complex was third in importance in 1989.

Pink Bollworm

Pectinophora gossypiella (Saunders) (Lepidoptera: Gelechiidae). The pink bollworm is of major importance in Arizona and California, but can be found in Texas, Oklahoma, New Mexico, Arkansas, and Louisiana (Henneberry 1986). This insect may affect the yield and quality of cotton in several ways, including shedding of squares and small bolls, increase of boll rot from larval feeding, reduction in seed weight and viability from larval feeding, and discoloration of lint by feeding and movement of larvae inside the boll. In addition, strength and maturity of fibers may be diminished as a result of larval feeding.

Cotton Aphid

Aphis gossypii Glover (Homoptera: Aphididae). Aphids cause yield losses in cotton by sucking juices necessary for normal boll development (Young 1969). Aphids also secrete a honey-like substance ("honeydew") which causes leaves to be sticky, and contributes to the formation of a black, sooty mold on cotton lint which lowers quality and causes problems in spinning. Until recently, the cotton aphid was considered a minor and sporadic pest of cotton. Increased usage of pyrethroid insecticides, which were ineffective against aphids in the late 1970's and early 1980's, and confirmed development of resistance to commonly used aphicides (O'Brien et al. 1990), have led to the emergence of this insect as a major problem in cotton production. Serious aphid infestations have developed earlier in cotton and in higher numbers in the mid-south during the past three years. These infestations have often remained throughout the season, and are difficult and costly to control (Hardee and O'Brien 1990).

Armyworms

Beet armyworm, *Spodoptera exigua* (Hübner) Fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae). Beet and fall armyworms tend to cause sporadic pest problems in cotton, but recently they have become a problem somewhere in the U.S. every year. Historically, when armyworms appeared on cotton they were known as foliage feeders, but their behavior has now changed to the point of feeding on squares, blooms, and bolls, as well as foliage (Smith 1989). Control with insecticides is costly, and the problem is amplified by their habit of feeding inside closed blooms which decreases the effectiveness of insecticides.

Whiteflies

Sweetpotato whitefly, *Bemisia tabaci* (Gennadius); Bandedwinged whitefly, *Trialeurodes abutilonea* (Haldeman) (Homoptera: Aleyrodidae). The bandedwinged whitefly occurs throughout the Cotton Belt, but the sweetpotato whitefly occurs on cotton primarily west of Texas. Both species can be a pest in cotton, especially in late season, and may create "sticky cotton" problems similar to, but often greater than, that of cotton aphids. Both species (especially the sweetpotato whitefly) are difficult and costly to control because of their distribution inside the plant canopy on the underside of leaves, and their apparent tolerance to all major insecticides (Butler et al. 1986).

Two Spotted Spider Mite

Tetranychus urticae Koch (Acari: Tetranychidae). A number of spider mites attack cotton and are capable of causing serious damage, but the two-spotted spider mite is most common (Trichilo and Leigh 1986a). Feeding by spider mites causes blotched and discolored leaves which may abscise prematurely in heavy infestations. Discoloration and leaf drop reduce yield by decreasing photosynthesis by the plant. Spider mites may occur in all areas of the Cotton Belt, but they usually are worse in the western U.S. Outbreaks of spider mites usually occur late in the season and are associated with dry, hot weather, and after insecticide applications have destroyed beneficial insects and mites. Chemical control is costly and difficult because of increasing resistance to available miticides (Leigh 1963).

Western Flower Thrips

Frankliniella occidentalis (Pergande) (Thysanoptera: Thripidae). Western flower thrips occasionally attack cotton after initiation of blooming with 300 thrips per bloom not uncommon. Feeding on flower bracts and pollen may result in premature bloom shed and incomplete boll development, with subsequent decreased yield (Terry and Barstow 1988). However, Trichilo and Leigh (1986b) suggest that western flower thrips are an important predator on spider mites in the western U.S.

Cotton Leafperforator

Bucculatrix thurberiella Busck (Lepidoptera: Lyonetiidae). The cotton leaf perforator is found primarily in Arizona and California where it thrives in hot, dry climates (Young 1969). It feeds on cotton leaves causing premature defoliation in heavy infestations, resulting in square and boll drop and subsequent loss in yield. Control with insecticides is difficult and costly due to its resistance to many insecticides.

Minor Insect Problems

Each year several minor insects are reported to occur in isolated areas of the U.S. Cotton Belt (Young 1969). Damage and losses due to these insects are grouped in Table 1 as "minor pests" and "new pests."

Cotton Square Borer

Strymon melinus Hübner (Lepidoptera: Lycaenidae). The cotton square borer is seldom of economic importance since its natural enemies usually hold it in check. Like the more important bollworm, the square borer consumes the contents of the square which causes it to flare and drop.

Garden Webworm

Achyra rantalis (Guenee) (Lepidoptera: Pyralidae). This insect is present in most years in some states, but chemical control is seldom exercised. They can be found feeding in terminals or on young leaves, usually enclosed in their webbing.

European Corn Borer

Ostrinia nubilalis (Hübner) (Lepidoptera: Pyralidae). Damage to cotton from this insect has been reported in several states in the southeast, especially in North Carolina after the Boll Weevil Eradication Program was completed in this state (Savinelli et al. 1986). Borers are known to enter the stalk 5 to 15 m above ground and burrow up through the center resulting in lodged plants and improper maturing of bolls. At the end of the growing season, larvae are also known to attack bolls in the middle third of the cotton plant.

Loopers

Cabbage Looper, *Trichoplusia ni* (Hübner) Soybean Looper, *Pseudoplusia includens* (Walker) (Lepidoptera: Noctuidae). The cabbage looper has been an occasional leaf feeder on cotton for many years, but the soybean looper was identified for the first time in 1989 feeding on cotton in several areas in the southeast (King et al. 1990). The concern for this development is that soybean loopers feeding on soybean are now resistant to most available insecticides.

Mexican Mealybug

Phenacoccus gossypii Townsend & Cockerell (Homoptera: Pseudococcidae). This insect has become a late-season pest of cotton since 1987 and seems to be spreading each year (T. F. Watson, Univ. of Arizona, personal communication). It is currently limited to spotty infestations in about 40,000 acres of cotton in Arizona and part of Texas. Damage occurs late in the season and can result in death of the plant from excessive numbers in terminals, as well as very heavy "honeydew" which aggravates the "sticky" cotton problem from whitefly feeding.

Saltmarsh Caterpillar

Estigmene acrea (Drury) (Lepidoptera: Arctiidae). These larvae usually feed on cotton foliage late in the season, primarily in western irrigated areas.

Stink Bugs

Brown - *Euschistus servus* (Say), Green - *Acrosternum hilare* (Say), Southern green - *Nezara viridula* (Linnaeus) (Heteroptera: Pentatomidae). Damage from stink bugs varies from year to year and from area to area. Feeding on bolls results not only in lower yields through a reduced number of harvestable locks, but also in lower quality of lint and seed (Barbour et al. 1989).

Yellowstriped Armyworm

Spodoptera ornithogalli (Guenee) (Lepidoptera: Noctuidae). This armyworm is a day-feeding insect which damages cotton by feeding on the leaves, usually in early season, and occasionally by boring into squares and bolls later in the season.

Current Challenges in Cotton Insect Management in the United States

We are currently operating in the U.S. with several challenges which will greatly affect our ability to produce cotton efficiently in the future. These include:

- Continuing increase in insecticide resistance: Without exception, all of the major cotton insect pests are confirmed or suspected of being resistant to all or some of the currently used insecticides.
- Loss of available insecticides: Several of our most important insecticides used for cotton insects have been removed from the market for environmental or legislative reasons, as well as from lack of interest by private industry because of re-registration costs.
- Cost of registration: The current estimated cost of registering a new product from initial testing to availability to the producer is estimated at \$40-50 million.
- Lack of new chemistry: Very few new products are in the testing stage by industry, and to my knowledge only one company is testing potential products with new chemistry.

- Current environmental issues: Public awareness and concern for food safety, global warming, water quality, and environmental safety are at an all-time high. We must, therefore, be cautious and judicious in our recommendations and use of agricultural chemicals to prevent environmental damage (real or imagined) and subsequent adverse publicity and litigation.
- Lack of alternative control strategies-methods: Other control measures, such as genetic control, use of microbials, pheromones, host plant resistance, beneficial insects, or a combination of these, are all in their infancy and offer few, if any, immediate solutions.

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Table 1. Cotton Insect Losses for 1989 for All States¹

Pest	Infested	Number of Acres				
		Above Treatment Thresholds	Insecticide Applications	Cost of one Application	% Yield Reduction	No. Bales Lost
Boll weevils	5,865,741	4,783,596	2.6	3.85	2.75	331,466
Lygus bugs	4,072,826	2,346,507	0.3	4.16	2.05	246,667
Bollworm/Budworms	7,478,934	4,683,150	1.8	7.14	1.87	225,115
Spider mites	2,659,204	1,599,112	0.2	11.02	1.11	133,838
Aphids	6,021,428	3,798,381	0.8	5.06	0.55	65,805
Thrips	6,581,397	3,593,701	0.5	4.09	0.36	42,782
Beet armyworms	1,194,911	529,996	0.1	10.47	0.15	18,629
Pink bollworm	416,775	350,505	0.2	8.94	0.14	16,438
Fleahoppers	4,404,730	1,032,670	0.1	3.09	0.11	12,951
Fall armyworms	584,400	170,336	0.0	7.80	0.03	3,596
Western flower thrips	2,198,300	158,857	0.0	7.36	0.03	3,388
Leaf perforators	234,000	109,000	0.0	9.04	0.00	267
Minor pests	1,004,227	371,727	0.1	9.86	0.05	5,741
New pests	319,805	181,705	0.0	8.96	0.03	3,223

¹ Modified from Head (1990).

Management of Cotton Bollworm and Tobacco Budworm Populations through Area-Wide Application of Nuclear Polyhedrosis Virus on Early-Season Alternate Hosts

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Abstract

When all of the early-season areas within a 100 square mile area of the Mississippi Delta were treated with a single application of the nuclear polyhedrosis virus from the bollworm *Helicoverpa zea*, pheromone trap data indicated the rate of increase of the population of bollworms and tobacco budworms, *Heliothis virescens*, was less in the treated area compared to control areas. The reduction in population was estimated at 25-38% fewer budworms and 19-31% fewer bollworms in the treated areas. Bioassays of plants indicated that only ca. 12% as much virus was deposited in the target areas compared to previous studies, and the loss of virus coverage was believed to have resulted in reduced control effectiveness. In cage testing areas, where 22% as much virus was deposited compared to previous studies, there was a 41% overall reduction in the numbers of emerging budworm/bollworm adults. Results of the study demonstrated the need for application and formulation studies prior to any future tests.

Introduction

Two Lepidopterous species, the cotton bollworm, *Helicoverpa zea* (Boddie), and the tobacco budworm, *Heliothis virescens* (F.), are major pests of cotton in the Mid- and Southeastern U.S. and serious pests of many food, fiber, and forage crops in the western hemisphere. Their continuing propensity for developing resistance to insecticides, and the increasing problems associated with the use of chemicals for their control, indicate an essential need for the development of alternative methods of management or control of these two pests. One such method is through the suppression of the first generation of adults that are produced in wild, early-season alternate hosts (Stadelbacher 1981).

The importance of several introduced and naturalized early-season host plants of bollworm/budworm in the delta of Mississippi in the buildup of the F_1 larval generation which subsequently invades cotton was discussed by Stadelbacher (1979, 1981). These investigations showed that a species of wild geranium, *Geranium dissectum* L., was the major alternate host in the area. Based on a quantitative study of larval and adult populations (Stadelbacher 1979), it was estimated that as many as 450,000 bollworm/budworm larvae and 17,000 adults were produced per hectare of this host. His studies indicated that moths emerging in the spring were restricted to and concentrated in early-season alternate host plants occupying less than 5% of the total rural area. The rationale of attacking bollworm/budworm populations during this first generation, and possibly the second, was later addressed by Knipling and Stadelbacher (1983). They envisioned that a 90% reduction in area-wide emergence in the first generation could be an effective management tool.

A simple dye method of marking bollworm/budworm populations emerging from areas of early-season weeds was used in a field study to demonstrate a reduction in moth emergence due to treatment with an environmentally safe, nuclear polyhedrosis virus (NPV) (Bell 1988). In a subsequent cage study, a single, hand-sprayed application of the bollworm NPV in water resulted in greater than a 90% reduction in emergence (Bell 1990a). Additional cage studies demonstrated that aerial applications of virus suspended in water to early season hosts resulted in similar reductions in emergence (Bell 1990b). All of these studies provided the basis for a pilot test conducted in the spring of 1990 to investigate the effect on bollworm/budworm populations when a nuclear polyhedrosis virus is applied over a large area during the period that bollworm/budworm are known to be developing on early-season alternate hosts. Here we report the results of that test.

Research Plan

The plan consisted of aerially applying a viral insecticide to all of the early-season alternate host plants of bollworm/budworm within a single area of 100 square miles (64,000 acres) and comparing the emerging adult populations to those in a similar untreated area, separated by a 10 mile buffer area. The 2 areas were chosen based on similarity of both crop and weed hosts of bollworm/budworm. The treatment area was located in parts of Washington and

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Sunflower Counties in the Mississippi Delta, between Leland and Indianola, Mississippi. This particular treatment area was chosen because a 3-year history of budworm/bollworm populations in the area was already available (Hayes 1990). The virus treatment (Elcar) the nuclear polyhedrosis virus from *Helicoverpa zea* was to be applied at a time of maximum immature seed production in a majority of the wild *Geranium* spp. in the test area. Data would then be collected to determine spray coverage, infection rates of larvae on pre-season wild hosts, persistence of the virus on the plants, the number and species of moths emerging from alternate hosts within the areas, and the number and species of the first bollworm/budworm adult populations invading cotton.

Obtaining data on spray coverage, viral persistence, and infection rates utilizes relatively standard procedures in insect pathology. However, the primary evaluation of the success of the wide area suppression tactic in an open and heterogeneous agroecosystem, where the target is a highly mobile pest like *Heliothis* or *Helicoverpa*, presents some serious challenges to standard scientific procedures. Available funding and practical considerations preclude the level of replication necessitated by the presumed plot to plot variability. For large-scale entomological studies, Schneider (1989) reviewed three approaches. The optimal approach was a 2-yr study with reversal of treatment and control sites in alternate years. In this approach both year and location serve as replicates, or more accurately, standards for comparison. It is common practice in other fields, such as water shed studies, to utilize historical data and reference sites as standards for comparison.

The evaluation design for the HNPV pilot test followed the design outlined by Schneider (1989). Two 100 square mile (10 mi X 10 mi) areas of the Delta were identified, one was designated the control area and the other the treatment area for yr 1. These designations will be reversed in yr 2. Historical data were already available for designated treatment area for year 1 from a long-term movement study conducted in approximately the same location from 1987-1989. In this previous study, both male adult and egg count data were taken and thus could be used to assess the impact of the HNPV treatment in 1990 (Hayes 1990).

Egg count data could be the most valuable information, since current economic thresholds may be based on egg numbers (no. eggs/plant) and the decision to treat is often based on egg counts (e.g., see Miss. Control Guide, Miss.

Coop. Extn. Ser.). However, collection of these data is labor-intensive and impractical on a large scale. During the early season, data analysis is complicated by the rapid changes in host attractiveness. Field to field variability is high since planting times vary among growers and is weather dependent. Until cotton reaches the pinhead square stage, oviposition is relatively rare. At the same time velvetleaf, *Abutilon theophrastii* Medicus, a frequent weed in early season cotton, will be heavily utilized by ovipositing females. Later, as cotton becomes more attractive, cultivation of fields eliminates much of the velvetleaf, which may result in increased utilization of cotton by ovipositing females.

Pheromone traps are extremely valuable sampling tools despite inability to ascribe an economic value to the number of moths captured on a day to day basis. Extensive studies of trap performance (Hayes and Coleman 1989, Lopez et al. 1988), have shown that trap capture data accurately reflect the relative abundance and fluctuations in the adult male populations in the immediate area. Also, while all trapping devices have inherent biases, they are far more reliable and consistent than human sampling efforts (Hartstack et al. 1978).

Both long-range and mesoscale movement of *Heliothis*/*Helicoverpa* play significant roles in area-wide control. For the treatment area, sampling of both adults and eggs was extended beyond the treatment boundary to assess the impact of migration. Previous studies (Hayes 1990) have shown that *Heliothis*/*Helicoverpa* can move as far as 12 miles and may typically move 2-5 miles per generation, depending on environmental conditions. Thus, the expectation is that the impact of HNPV application will be most apparent in the center of the treatment area and will dissipate at the borders. However, spatial heterogeneity in the area is high and can obliterate the impact of treatment. Additionally, any indicated suppression in a small treatment area is likely to be diminished from one generation to the next due to migration.

The untreated extension of a treatment plot is more likely to be similar in host and pest composition to the treated plot than the control area, but it is not independent of the treated plot because they share a border and are directly influenced by migration (emigration and immigration).

The impact of treatment will be apparent in deviations in trap capture patterns between years (in the treatment area) and within-year between treated and untreated areas, both the control and untreated area beyond the actual treatment plot. It is unlikely that any two, 100 square mile areas are similar in crop or pest patterns; however, the capture patterns should be more consistent with the treated area when compared to the previous year patterns. Also, in year 2, the control plot will become the treatment plot, and the 1990 data provide the standard for comparison in 1991.

To determine the level of suppression where spatial heterogeneity is high, the overall rate of increase in the area from parental to F_1 generation is a critical measure. An estimate of the actual rate of increase can be obtained from trap capture data.

Public Information Strategy

Since no large, populated, and non-crop area was known to have been treated with a microbial pesticide in the past, the reaction of the public to the project was of utmost concern. We believed, however, that an informed public would be an approving public. The strategy for the public information campaign was developed jointly by USDA scientists involved with the project, the USDA, ARS Information Office, Delta Council, and personnel of Sandoz Crop Protection, Inc. This process began with the preparation of an information brochure and a slide presentation prior to the first meeting with those not involved with the project. The first meeting was held ca. 8 months prior to the beginning of the test. The purpose of this meeting was to inform those persons identified as the most likely to be approached for comment by the general public or the media of the details of the test, as well as the safety of the project. The meeting included a cross section of persons, such as Mississippi State regulatory officers, large-scale farmers, congressional representatives, scientists working in similar areas of study, environmental and health regulatory personnel, representatives of action groups, extension and university personnel, and heads of research departments. This core group would be used if any pre-test media publicity occurred in which comments from other informed persons were needed.

Approximately 5 months before the test, a meeting was arranged with local physicians to acquaint them with nuclear polyhedrosis viruses and answer their safety

questions. After that meeting, all of the physicians in attendance agreed to allow their names to be used as contacts for any questions from media sources and from their patients. About the same time, meetings were arranged with local city and county officials to present the proposed test to them. These information contacts were made by a well-known local city councilman in the area after he became familiar with the project.

A date approximately 3 months prior to the beginning of the test was chosen as the date to begin informing the general public of the pending test. A national press release was distributed to the media from 1 to 3 months prior to the test, and contacts were made with the local media to supply them additional information regarding the test if they desired. Many presentations were given during that same period to local civic clubs, garden clubs, environmental interest groups, and private interest groups. The virus to be sprayed, its safety, and how it was to be used was discussed at all presentations. Special meetings were also held with specific groups of invited participants working in local agriculture, such as consultants, aerial applicators, and extension personnel.

The last month before the test was devoted specifically to contacting those persons living within the test area. To accomplish this goal, each residence in the test area was visited, given an information brochure, and the project was discussed when questions were asked. The brochures also contained invitations to meetings specifically for the residents and general public to discuss the test or ask questions. Two meetings were held, but none of the residents attended. A special effort was made to contact and visit the five catfish producers in the test area. After learning more about the project, and specific safety testing of the virus on possible effects on catfish, all of the producers gave their permission for viral treatment in and around their pond areas. No complaints or negative publicity was detected or received throughout the entire test.

Methods and Materials

Virus

The NPV from *H. zea* (Elcar) was provided by Sandoz Crop Protection, Inc. The virus was standardized prior to delivery and contained 4×10^9 polyhedral inclusion bodies (PIB)/g. The Elcar was supplied in 20 lb lots. Although the virus was bioassayed during the standardization procedures by Sandoz personnel, additional bioassays were conducted at this laboratory and by other cooperators to verify its activity. Our bioassays were conducted using methods described by Dulmage et al. (1976) as modified by Bell and Romine (1986).

Application

The virus was applied both by aircraft and by trucks equipped with mist blowers. Both methods of application were calibrated to deliver virus at a rate of 40 larval equivalents (40 L.E.) or 2.4×10^{11} PIB in 2 gallons of water per acre. Two aircraft (Cessna Ag Trucks) and pilots were supplied by USDA, APHIS Aircraft and Equipment Operations, Edinburg, Texas for application services. The aircraft were calibrated at their home base to deliver 2 GPA and 50-60 droplets per square centimeter with a VMD of 300 micron. This application rate was shown in a previous study to provide good spray coverage of the wild geranium (Bell 1990b). The 100 square mile area was divided into 20 plots containing ca. 5 square miles each in order to have a workable size area for treatment. Aerial photos (USDA, ASCS, Aerial Photography Field Office, Salt Lake City, Utah) were used to prepare booklets with 1 plot/page for the pilots use during the application. Additional maps were prepared and supplied to all aerial applicators working in the treatment area, who were then notified which areas the aircraft would be treating as the application proceeded. A treatment operations headquarters was set up at the municipal airport at Indianola, Mississippi, located near the northeast corner of the test area. This facility was chosen due to the availability of water for mixing, aviation fuel, and a hard-surface runway.

The virus for application was mixed with thorough agitation in 1000 gallon tanks, preparing 600 gallons each time to allow space for mixing. The tanks were equipped with gasoline-driven pumps and normal aircraft fittings for

sprayer loading in minimum time (200 gallons per 3 minutes). Since the plan was to treat only the possible alternate host habitats, the pilots attempted to treat only along field edges, borders, fallow fields, treelines, etc. Water-sensitive cards were placed randomly among the weeds to determine sample spray coverages in some test areas. Aerial application began on 24 April, a time believed to be ca. 7 days prior to the maximum overall seed production in the *G. dissectum*, the primary alternate early season host of bollworm/budworm (Stadelbacher 1979). All host areas treated by aircraft within the test area, except the fallow fields, were treated by 8 May, although much of the application was done during weather conditions, primarily too much wind, not favorable to spot spraying sites. Due to a series of early spring weather fronts, farmers in the area were late in tilling many of their fields. This resulted in an unusual amount of weed areas where it was questionable as to whether or not they should be treated in our test. During the period of 8-11 May, applications were made to fields that were not treated during the previous application, with the pilots determining which fields would be treated based on weed populations and the likelihood that the particular area would be plowed in the near future. As shown in the spray data, the aircraft applied a total of 1,653 lbs of Elcar in 25,020 gal of water. This volume would treat ca. 12,510 ac, or 19.5% of the treatment area.

Application by the truck-mounted mist blowers was done between 30 April and 4 May. These blowers were calibrated to deliver 2 gallons per acre from the side of the truck driven at 5 MPH with a 60-ft swath width. This application procedure was used to treat along the major roadways within the test area, a distance of 335 miles total. Although these areas are known to be major sites for geranium growth (Stadelbacher 1982), they are also generally more difficult to treat by aerial application, either because of vehicle traffic or nearby power lines. The trucks applied a total of 145 lb of Elcar along the roadways, enough to treat a total of 1,097 acre.

Evaluation Techniques

Field bioassays

Bioassays were made of field collected material to estimate the efficiency of the spray application and the persistence of the virus on the wild geranium. To estimate the quantity of virus on the alternate hosts, plant terminals were cut at random on various days from *G. dissectum* in 8 plots in the treatment area as soon as possible after the aircraft completed the treatment of the plot. The terminals were then fed to 6-day-old tobacco budworm larvae (avg. wt.: 21.6 mg) for a period of 48 hr (72 terminals from each location), after which the larvae were then placed on artificial diet. Larval mortality was recorded 10 days after the beginning of the feeding period. Similar samples were taken at the 3 locations used for the cage study below, plus the sampling procedure was repeated 1, 2, 3, 5, 7, and 9 days after application to estimate the persistence of the virus on the plants. A final bioassay was conducted on 29 May to determine the residual virus on the weeds. Random samples of remaining wild geranium were collected and fed to larvae as before, with 144 larvae fed material from treated plots and 144 fed material from untreated areas.

Cage study

The methodology used for the cage tests was similar to that used in a previous study (Bell 1990b) with some modification. Plots of early-season weeds, primarily wild geranium, were chosen within the treatment area at 3 locations and measured for cages in late March. Plot edges were mowed to facilitate cage installation. Plots at each location were arranged in RCB design with 3 replicates of 2 treatments each plus an untreated control. One treatment consisted of NPV applied aurally only on the date that the test area was treated. The second treatment at each location received the aerial application, plus a ground application of the virus at similar rates, to test the possibility of a timing effect on control results. Aerial applications were made in plot numbers 5, 10, and 15 (the areas in which the cage tests were done) on 26 April, 30 April, and 4 May, respectively. The untreated control plots were covered with plastic sheeting during application. Cages made of plastic insect screen (4m X 8m X 2m) were placed over each plot and secured on 8 May. Periodic external inspections were made to assure that the cages remained secure. Visual examinations for the beginning of moth emergence were also made from outside the cages. Searches were conducted daily within the cages after the first budworm/bollworm

moth was observed, and moths were captured and removed. Numbers, species, and sex of the moths were recorded. The data were analyzed by the procedures of the Statistical Analysis System (SAS Institute 1985) using ANOVA, and means were examined using the method of Least Significant Difference.

Adult *Heliothis/Helicoverpa* sampling

Pheromone traps, standard 75-50 hardware cloth cone traps (Hartstack et al. 1979), were used to monitor the relative abundance and fluctuations in the adult male *Heliothis/Helicoverpa* populations in the treatment and control areas. In both areas, four trap locations (1 trap/sp./loc.) were identified near cotton fields within each 1 mile interval/radius from the center; at radii from 1-5 miles in the control plot, and from 1-10 miles in the treatment area, to assess the impact of migration on the treated area (encompassed in radii 1-5). The traps were baited with either *H. zea* lure (Hercon Laboratories, Inc., Emigsville, Pennsylvania) or *H. virescens* lure (Scentry, Inc., Phoenix, Arizona). Depending on availability of an accessible cotton field, attention was given to spacing trap locations in different quadrants. A trap location consisted of 1 trap/sp. separated by ca. 100 meters, placed at the edge of a cotton field along an accessible roadway. Because fields are frequently cultivated and roadsides are often mowed or burned, traps were placed near power poles and in other protected sites.

Traps were routinely monitored from 1 April to 1 August, which encompassed and/or included the flight of the parental, F_1 and F_2 generations. During that time, traps were emptied three times per week (MWF), and the captured moths counted and recorded; lures were replaced biweekly. Traps were repaired as needed, and the area under each trap was kept clean of vegetation.

Heliothis/Helicoverpa egg sampling

In both control and treatment areas, one to three cotton fields in the neighborhood of each trap location were searched routinely for eggs (and occasionally larvae) during the F_1 generation. Multiple sites were sampled to ameliorate the site-to-site variability in crop phenology. The developmental stages of cotton ranged from cotyledon to pinhead square at the onset of sampling to pinhead square to flowering at the end of sampling. Velvetleaf was initially prevalent in many fields and was sampled along with cotton. Some corn and velvetleaf-only sites were sampled in order to assess more accurately the overall rate of oviposition in each area.

Each field was searched, by terminal inspection, for 30 minutes at 2-3 day intervals. All eggs encountered were collected in 30 ml plastic cups, kept separate by location, and returned to the laboratory for processing. Eggs were counted and all (if <20) or a portion (not less than 20%) were set up on diet to rear for species identification.

The control area was arranged similarly except that the traps did not extend outside the 100 square mile area. Each test area contained 24 trap locations, and there were 17 trap locations in the extended area surrounding the treated area for a total of 130 traps. The traps were baited on 14 March (Julian date 75) and trapping continued throughout the entire test. All traps were checked 3 times per week and the numbers of moths recorded. The lures were replaced every other week.

In addition to the estimation of the emerging population by adult trapping, attempts were made to estimate the number of adults by counting the egg deposition on early hosts and cotton within the test areas. This method required visually checking plants for a total of 30 minutes in each sample area and recording the numbers and relative population of species of budworm/bollworm eggs located in a fixed time.

Personnel Requirements

The number of personnel needed for this test was quite extensive. During the application period, 3 ground crew persons plus 2 pilots worked at the airport, while an additional 2 persons marked the corners of the plots on the ground when needed. Two persons were needed for conducting the bioassays during the entire test period. The ground application with the mist blowers required a supervisor and 3 additional persons during that week only. Setting up, baiting, and checking the pheromone traps required 4 persons plus a technical supervisor. Checking the plants for presence of eggs during the emergence period of the moths that developed as larvae on the early season hosts required 7 persons. The cage studies required 2 technical supervisors and 2 additional persons. To conduct the test, a total of 21 temporary persons was employed at various times; in addition, 3 supervisors and 4 technical supervisors were also needed.

Results and Discussion

Field Bioassays

When *G. dissectum* terminals were randomly collected from 8 different plots immediately after aerial application, and then fed to 6-day-old tobacco budworm larvae for 48 hours, mortalities at 10 days averaged 75.1% and ranged from 67.7% to 88.7% compared to a background mortality of 9.3% when larvae were fed terminals from untreated areas. Although the mortalities of larvae fed treated terminals were significantly greater than when larvae were fed untreated terminals, the 75.1% mortality was also significantly less than that reported in a previous study (Bell 1990b). In that study the treated area was in an open field, and the application was made in broadcast fashion and not to a strip target area. When those terminals were tested, larval mortalities averaged 95.7%. The random samples tested here were taken from along tree lines, field borders, etc. and not from open fields. The difference in the concentration of virus required to produce 75% mortality in a laboratory bioassay (ca. 760 PIB/ml) compared to the dose that results in a 96% mortality (ca. 6130 PIB/ml) indicates a reduction of ca. 88% in virus deposition on the target hosts in this study compared to the earlier application test. This lack of virus on the target hosts was also indicated by the numbers of droplets found on water-sensitive cards. A similar application rate and droplet size in the earlier test resulted in an average of 54.4 droplets per cm², whereas in the present test, there was an average of 3.9 droplets per cm² on 20 cards placed at random in strips of weeds within the test areas, indicating a 93% reduction in droplets hitting the plants.

In areas where the cage tests were conducted, water-sensitive cards contained an average of 28.2 droplets per cm² on 30 cards placed within the treatment area (10 cards per area). The virus was applied in these areas as a broadcast spray, sometimes from a higher altitude due to the presence of nearby trees. Although the number of droplets on the cards indicated increased coverage compared to the random samples, it was still only ca. half the 54.4 droplets deposited in the previous study. When 6-day-old tobacco budworm larvae were allowed to feed on the terminals from the cage test areas for 48 hours, mortality at 10 days averaged 81.0%, only a 6% increase compared to the random samples. The difference in the viral concentration required to produce 81% mortality in a laboratory

bioassay (ca. 1305 PIB/ml) compared to that resulting in a 96% mortality (ca. 6130 PIB/ml) indicates a reduction of ca. 78% in virus deposition on the target hosts in this test compared to the previous application study. Although the numbers of droplets were reduced by only ca. half, the bioassay data here indicate that the amount of virus deposited on the plants was reduced by almost 80%. Mortality due to viral infection at various times after application and the indicated persistence of the virus on the plants are shown in Fig. 1. When the larvae were fed on terminals collected at 1, 2, 3, 5, 7, and 9 days after treatment, viral mortality averaged 77, 69, 64, 57, 41, and 38 percent, respectively. The original activity remaining (OAR - obtained by mortality each day being compared to the mortality on day 0) on those dates after application was 95, 85, 79, 70, 50, and 47 percent, respectively. This persistence compares very favorably to the data reported in the previous aerial application test (Bell 1990b).

When wild geranium collected from the treated area on 29 May, 18 days after the end of all spraying, was fed to larvae as before, only 5% of the larvae died from NPV. Samples from outside of the test area produced no viral mortality. Very little of the wild geranium remained on that date.

Cage Study

The emergence and capture of *H. virescens* and *H. zea* adults in the cages are illustrated in Fig. 2. There were no differences between treatments due to the date of application. Since the Date*Treatment error component was not significant, a simplified ANOVA was performed across the 9 replicates for RCB design. The analysis indicated that both of the viral treatments significantly reduced moth emergence compared to the control (Table 1); however there was no difference between the 2 virus treatments. There was a 41% total overall average reduction in emergence in the cages treated by aerial application alone, and a 50% average reduction in cages treated by air plus a treatment using hand sprayers on 10 May. These results indicate much less effect than in the previous tests where the least overall reductions have been ca. 88% (Bell 1990b). In the previous study, however, the moth emergence was reduced only by 64% when the virus dosage was halved (20 L.E./ac). The bioassay data in the cages indicate that the aerial application resulted in ca. 22% as much virus on the plants in this study as in the previous

study. If these are factual indications, then the 41% reduction in moth emergence in this study would be reasonable. These data all indicate that deposition of the virus to the target area was a major problem in this test, even in the cage test areas where application was somewhat easier than in other host plant habitats.

The average number of moths emerging in the untreated cages in this test (9.6/cage) was less than the average captured in the earlier study (25.3). This was expected since the cage areas used for the earlier tests were treated with insecticide to reduce predator and parasite populations (Bell 1990b). In the present study, the total number of moths captured in individual untreated cages ranged from 5 to 17, and the number in cages that were aerially treated ranged from 2 to 17.

Adult *Heliothis/Helicoverpa* sampling

Visual inspection of the trap capture patterns revealed deviations from expected in the treatment area (1990 treated) compared to the previous yr (1989 treated), the control area, and 1990 untreated (Figs. 3 and 4). These graphs show the mean counts per day, by species, within the different areas. The vertical dotted lines define the generations: N_1 = the first generation to emerge in the spring which lays its eggs on early-season wild hosts, often referred to as the P generation; and N_2 = the first generation to move into cotton, often referred to as the F_1 generation. The egg data along with the trap data were used in determining the positioning of these dates. Egg data can be more reliable than trap data because egg deposition usually drops to zero between generations while trap captures "bounce", and rarely return to zero after the first (P) generation.

Under normal conditions (see Fig. 3, 1989) trap captures for both spp. increase with each successive generation until mid-season. From the parental to F_1 generations peak mean captures/day may increase by 2-fold. In the treatment area (Fig. 4) *H. zea* showed an initial increase during the F_1 generation; however, *H. virescens* failed to reach a mean capture rate/day during the F_1 that exceeded the parent (P) generation peak. At the same time, in the adjacent untreated area, both *H. zea* and *H. virescens* patterns appear normal, i.e., peak mean captures/day during the F_1 generation exceeded the P generation peaks. In the control area, the mean captures/day peak exceeded the P generation

peak, and continued to climb after the treated and untreated plot values showed a decline. Trap captures of *H. zea* in the treated plot dropped off dramatically on 6 June, while the rate of decline in the untreated plot was more gradual. Trap captures of *H. virescens* in the control area were relatively low in both generations (compared with the treated and untreated plots) and reached nearly equal peak values in the P and F₁ generations.

Data collected in the F₂ generation suggested that activity in the control plot is normal, i.e., mean captures/day will exceed those in the previous generation (F₁). However, activity in the treated and untreated plots remained relatively low. Further trap capture data are needed, however, to determine whether the apparent impact on both spp., as measured by deviations in trap capture patterns, will be felt in the subsequent generation(s).

Correlations analysis of 1990 trap capture patterns revealed no significant differences, although the correlation coefficients differ in anticipated directions (e.g., for the P generation, *r* ranges from 0.96 to 0.99 for treated, untreated, and control; for the F₁ generation *r* ranges from 0.89 to 0.96). It is unlikely that correlations analysis would expose the impact of a systematic suppression tactic such as use of HNPV, since the population should show a characteristic cycle of emergence and activity but at much reduced densities.

Calculations of rate of increase (*r*₁) between the generations confirmed the visual assessments of trap capture data and were perhaps the most indicative data collected. These values are calculated by taking the natural log of the total number of moths captured in generation 2 divided by the total number captured in generation 1. The rates of increase (*r*₁ values) between the first two generations are given for each species (Figs. 3 and 4). In general, the rate of increase in all plots in 1990 were lower than those measured for 1989, and the rate of increase for *H. zea* in both years was higher than that for *H. virescens*. In 1989, *H. virescens* increased by 38%, and *H. zea* increased by 95%. These increases are typical from generation to generation over the season through at least the F₃ generation.

The rates of increase of both species in the treated plot was lower in comparison than the increases in the untreated and control (Fig. 4). Both species realized lower rates of

increase in the treated area compared to the expected rate of increase based on 1989 results and compared to either the 1990 control or untreated extension of the treated area. The rate of increase for *H. virescens* in the treated area was only 13% compared to 38% for the control and 51% for the untreated area. The rate of increase for *H. zea* in the treated area was only 36% compared to 55% for the control area and 67% for the untreated area. The treated area produced 38% fewer *H. virescens* and 31% fewer *H. zea* overall than the untreated area, and 25% fewer *H. virescens* and 19% fewer *H. zea* than the control area.

Neither linear nor non-linear regression analysis revealed significant relationships between mean captures of either species and distance from the center of the treated area. This result is not surprising given the high degree of spatial heterogeneity on the area, and also the high degree of temporal heterogeneity imposed by the elongated applications period (21 days). Analyses that account for this heterogeneity are planned.

Conclusions

The results of this test indicate that the single virus application reduced the adult *Heliothis virescens* population emerging from early season alternate hosts by ca. 25-38%, and the *Helicoverpa zea* population by ca. 19-31% in the 100 square mile area. In cage test areas where there was somewhat increased virus coverage compared to the remainder of the test area, the overall bollworm/budworm adult emergence was reduced by 41%. Although the treatment failed to reduce the adult population as much as was expected, these results were still encouraging. The indicated reduction in the number of moths was understandable when all factors of the study were taken into consideration. The primary factor was the lack of spray coverage, and a secondary factor was the timing of the application. Although aerial application studies had been done in which the virus was applied to alternate host areas, this test was different in that much of the application had to be done under windy weather conditions. Bioassays were very informative in indicating the presence of the virus on the plants, and based on that data, the reductions in the populations was comparable with prior tests. Although timing was less a factor than spray coverage, an application made over a 21 day period would be considered too long for most seasons when the growth of the alternate hosts is

considered. The length of time needed to apply the virus in this test could easily be corrected by increasing the number of spray aircraft.

In general, we feel that the test reported here accomplished some valuable goals, e.g. the education of and acceptance by a large segment of the general public regarding the use and safety of microbial insecticides in insect pest management systems. We further believe that the factors which probably reduced the effectiveness of the virus application in this test can be overcome, and that, following further testing, this method of pest management will be proven effective in the future.

Acknowledgment

Many persons played instrumental parts in this pilot test, without whose aid the successful completion of this test would have probably been impossible. Many personnel of the Mississippi Agricultural and Forestry Station aided in the public information campaign as well as provided support. Sandoz Crop Protection personnel aided in several ways prior to and during the test. We wish to especially acknowledge and thank those named below as well as countless others not named here who gave their time and support during the test.

D.L. Boykin, USDA, ARS
J.R. Brazzel, USDA, APHIS
D.W. Hubbard, USDA, ARS
C.M. Ignoffo, USDA, ARS
R.G. Jones, USDA, APHIS
M.T. Misner, USDA, ARS
E.M. Morgan, Delta Council
R.M. Parry, USDA, ARS
B.D. Radsick, USDA, APHIS
J.C. Schneider, Mississippi State Univ.
B.F. Tanner, USDA, APHIS
S.A. Thomas, USDA, ARS

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Table 1. Number of moths emerging per cage after treatment with nuclear polyhedrosis virus (NPV) (average of 9 cages per treatment)

Treatment	<i>H. virescens</i>	<i>H. zea</i>	Totals
Untreated	8.11 a ¹	1.44 a	9.56 a
Aerial Application	5.00 b	0.67 ab	5.67 b
Aerial and Ground Application	4.70 b	0.11 b	4.78 b
LSD	3.04	1.08	3.32

¹ Numbers in columns not followed by the same letter are significantly different at the 5% level

Viral Activity in Cage Testing Area

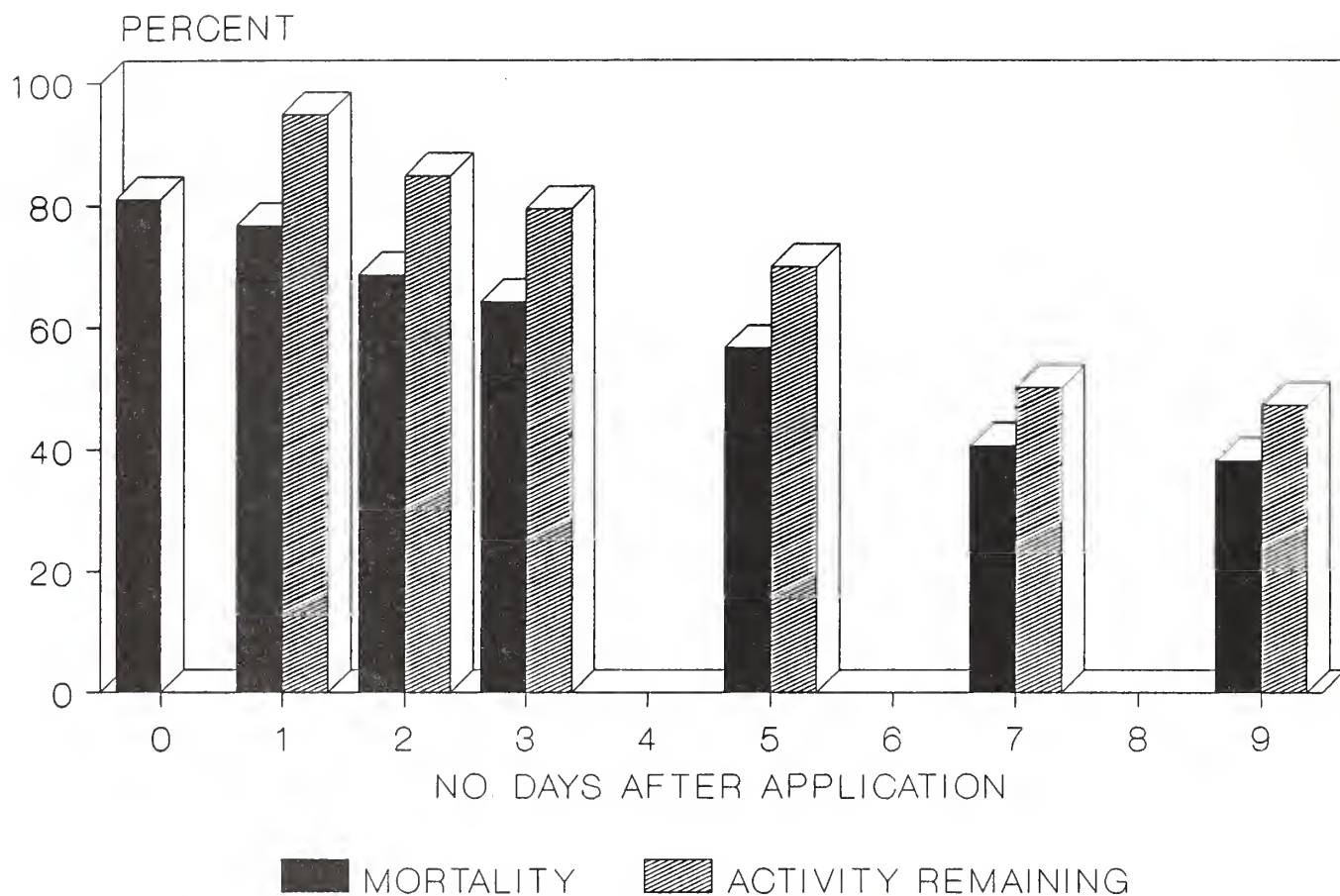
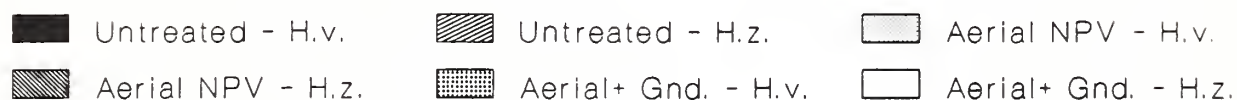


Fig. 1. Amount of active virus remaining at indicated number of days after application based on mortality of 6-day-old larvae 10 days after feeding for 48 hours on treated plant terminals (avg. 3 reps). Activity remaining is comparison of viral activity to activity on day 0.

Heliothis Emergence



Adults per 3 cages.

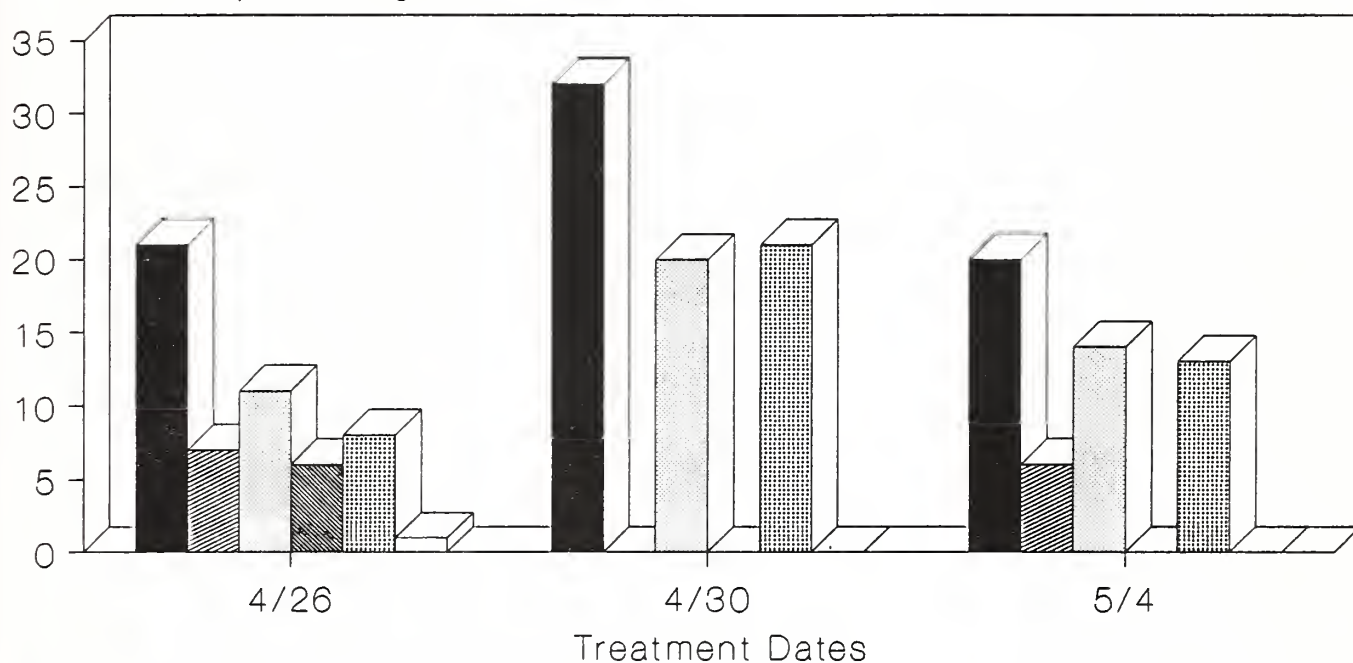


Fig. 2. Number of adult moths emerging in cage areas treated with 40 Larval Equivalents of NPV/acre on 3 different dates.

HNPV TREATMENT AREA 1989

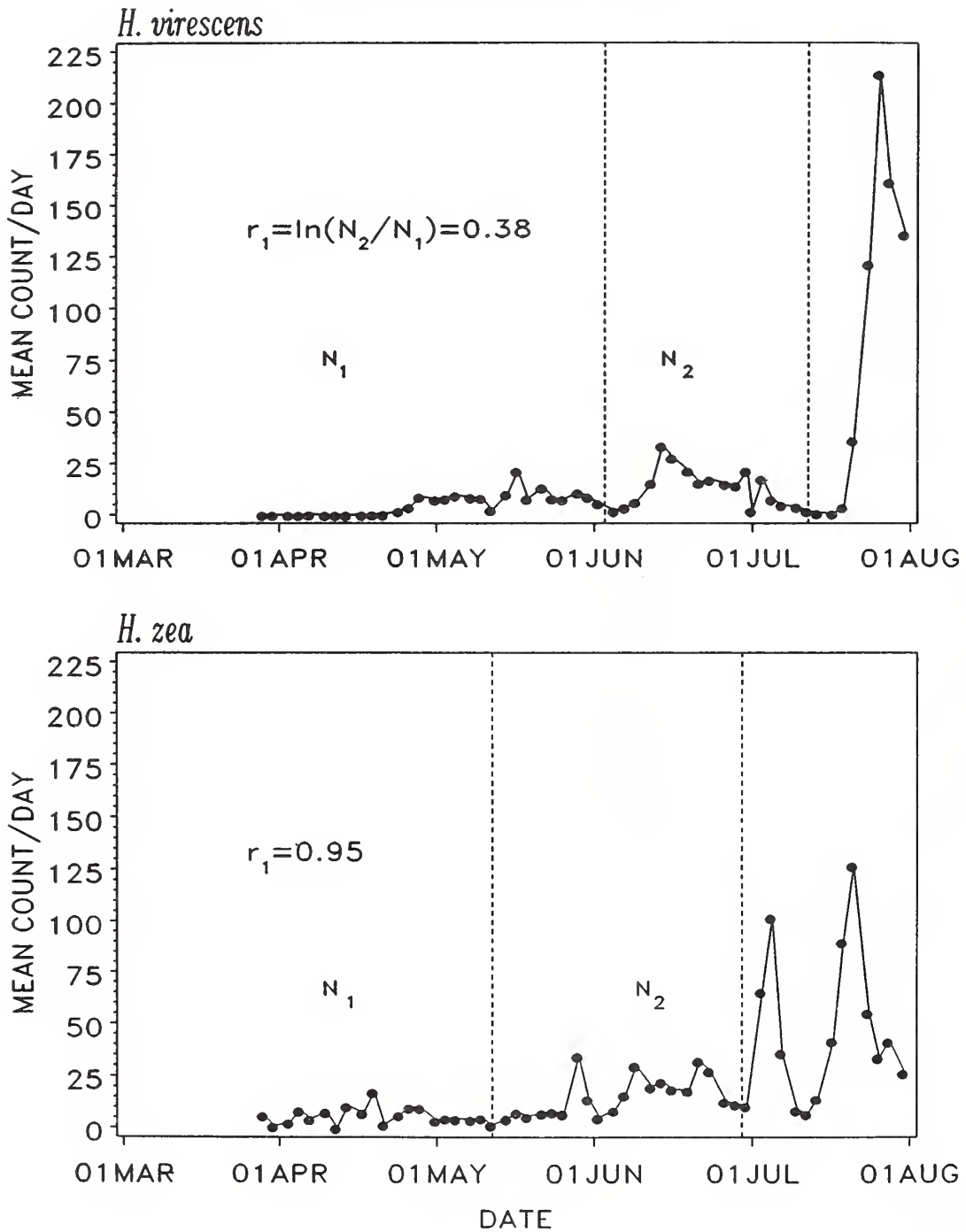


Fig. 3. Captures and rates of increase (r_1) of budworm and bollworm adults in 1989 in area used for treatment in 1990.

HNPV TREATMENT AREAS 1990

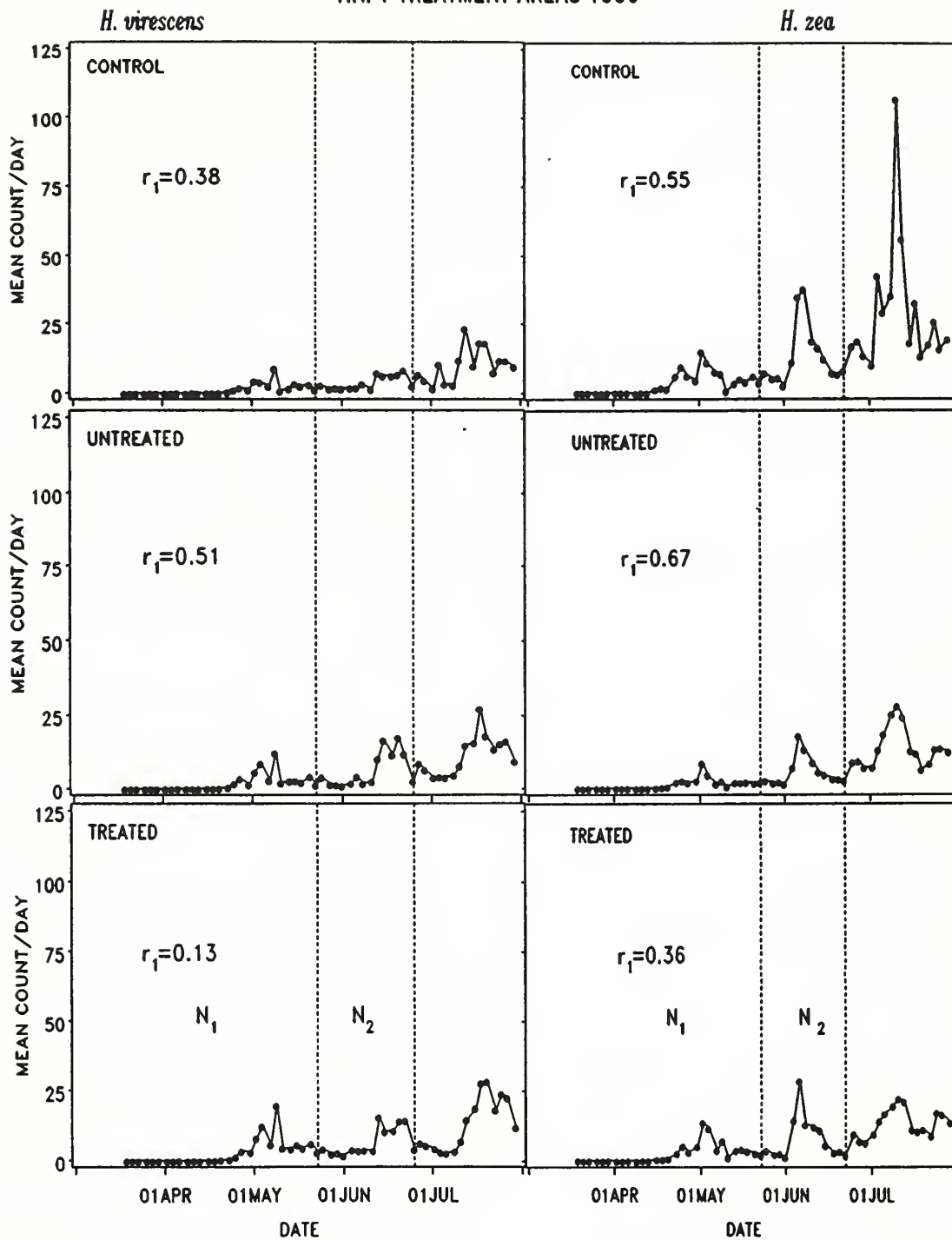


Fig. 4. Captures and rates of increase (r_i) of budworm and bollworm adults in treated area compared to the control area and the untreated area immediately surrounding the treated area (untreated) in 1990.

Production and Application of *Trichogramma* in the former Union of Soviet Socialist Republics

Sh. M. Greenberg¹

In the former U.S.S.R., the scale of biocontrol applications has increased dramatically from 200,000 to 39,000,000 ha in the past 30 years. The areas are expected to reach 48.5 million ha in 2000 and 55 million ha in 2005 (Bondarenko, Voronin and Greenberg 1979; Novoxhilov 1989).

Trichogramma is the main means of biocontrol of the lepidopterous complex on cereal, leguminous, technical and vegetable crops and perennial grasses. Large scale investigations and production evaluation of *Trichogramma* effectiveness in orchards and vineyards have been carried out. In the recent 5 years, it has been annually applied on 60-65 % of the areas (in 1988 - on 16.5 million ha) protected by active biocontrol (Greenberg and Nikonov 1988). In the near future, i.e. in 2000, the former U.S.S.R. plans to increase *Trichogramma* application volume 2.5 times. It is promoted by such factors as the simplicity of laboratory rearing, ability to accumulate quickly at rearing and release, the use of the parasite to eliminate pests on a nonharmful stage of their development, and high biological and economic effectiveness of the entomophage in a number of the former U.S.S.R. regions. It has been established by the All-Union Institute of Biological Methods in Plant Protection (AUIBMPP) and All-Union Institute of Plant Protection (AUIPP) that scientifically grounded and timely application of *Trichogramma* in the regions favorable for its activity allows elimination of up to 60-80 % of pest eggs and increases winter wheat yield 1.7-2.0 centners/ha, corn 1.8-2.3 centners/ha, sugar beet 20-35 centners/ha; and cabbage 20-30 centners/ha (Fadeev and Greenberg 1985). *Trichogramma* production biofactories have been built and are functioning successfully at present. Research and production experience has been accumulated. *Trichogramma* is a good test object and research results can be used to reveal regularities for production and application of other entomophages.

The experience in *Trichogramma* research accelerates the development of a new branch - commercial entomology - similar to research experience on *Drosophila* which promoted developments in genetics.

Home and foreign experience demonstrates promising abilities for *Trichogramma* application against lepidopterous pests. However, wide variability of the data obtained

in experiments and during practical usage of *Trichogramma* introduces a set of new tasks for science. They are related to critical reevaluation and improvement of the existing *Trichogramma* production and application technologies. Under modern farming conditions phytosanitary problems become more complex. Thus, *Trichogramma* research aspects can't be considered without taking into account peculiarities of host-parasite relationships in different agrobiocenoses. Transition to the commercial *Trichogramma* production technology has to interact with biological and ecological changes both of the entomophage and its laboratory host. Genetic consequences of insect mass rearing have not been evaluated properly. It is necessary to establish the role and to determine the place of *Trichogramma* in integrated pest management (IPM). To solve the above mentioned problems and to get permanent high effectiveness of *Trichogramma*, it is necessary to intensify fundamental and applied studies on the problem by attracting different discipline specialists (entomologists, ecologists, physiologists, biochemists, geneticists, mathematicians, engineers). In the former U.S.S.R., 45 researchers from 15 institutions deal with the *Trichogramma* research project.

Selection of effective species plays considerable role in the use of *Trichogramma* in programs of biocontrol of noxious organisms. In the past 20 years, a revision of *Trichogramma* genus in the former U.S.S.R. fauna has been completed. Twenty-five *Trichogramma* species have been revealed and described, and key tables have been composed (Sugonyaev and Sorokina 1975, 1976; Sorokina 1986). Species promising for a number of regions have been determined: *Trichogramma evanescens* Westw., *T. pintoi*, *T. voegele*, *T. semblidis* Gir., *T. principium* Sug. et Sor., *T. cacoeciae* March., *T. embryophagum* Htg. The first four species are, as a rule, the inhabitants of field agrocenoses, the latter two species are encountered in perennial grasses. *T. evanescens* mainly parasitizes eggs of Pyralidae and Noctuidae; *T. pintoi*, eggs of cutting noctuids. These species are ecologically plastic and develop at 18-30°C, relative air humidity 60-90 %. *T. semblidis* is a hygrophilic species, promising against Noctuidae, *Cossida nebulosa*, *C. nobilis*, and *Pegomyia heosciami*. *T. principium* is xerophilic and resistant to high temperature. It prefers noctuid eggs and is effective on cotton under conditions of Middle Asia. *T. cacoeciae* and *T. embryophagum* parasitize eggs of Tortricidae, *Malocosoma neustria*, *Orgia antiqua* and others. *T. cacoeciae* is hygrophilic (70-80 % RH) and prefers moderate tempera-

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tures (18-23°C), *T. embryophagum* is xerophilic 40-60% RH) and develops optimally at high temperatures (26-28°C). Biochemical criteria of taxonomy have been developed in the former U.S.S.R. for economically important *Trichogramma* species (Yazlovetski et al. 1981).

Trichogramma effectiveness is, to a considerable extent, determined by its quality. In AUIBMPP it has been proposed to evaluate quality using the united quantitative criterion (D), which unites 4 main *Trichogramma* indices: surviving ability, sex index, and fecundity and activity for search of host eggs (Greenberg, Mencher and Podberezhskaya 1979). *Trichogramma* standards differing according to the quality class had been developed (Greenberg, Podberezhskaya and Mencher 1980a, 1980b). Dependence has been revealed [1] between the united quality criterion and the expected biological effectiveness of *Trichogramma* in the field (E) under optimal hydrothermal environmental condition (Table 1).

A system has been created in which *Trichogramma* quality is evaluated by the integral index under a certain environmental regime. It includes 7 biological parameters of the entomophage: ability to parasitize, ability to survive, deformed individuals, sex index, reproductive abilities, migrational abilities, and searching abilities (Chernyshev et al. 1986).

The selection of laboratory hosts is an important technological problem during *Trichogramma* mass production. The Angoumois grain moth (*Sitotroga cerealella* Oliv.) used at present in the former U.S.S.R. as *Trichogramma* laboratory host doesn't completely meet nutritional requirements of larval parasitoids both in egg size and their biochemical composition (Ageeva et al. 1978). Under long term rearing, the size of the parasite decreases as well as female searching capacity. Proper selection of the laboratory substrate has great potential to increase *Trichogramma* application effectiveness. There are several research possibilities to solve the problem such as selection of effective laboratory hosts reared on artificial nutritional diets and development of artificial nutritional substrates (Greenberg and Yazlovetski 1983). Data are scarce in literature from the former Soviet Union and foreign literature on comparative quality evaluation of *Trichogramma* reared on different hosts. They are also difficult to compare since they are expressed by many indices. It has been established that the united quality criterion of *Trichogramma* bred on cabbage moth

(*Mamestra brassicae* L.) eggs constituted 0.96, on the flour moth (*Ephesia kuehniella* Zeller) - 0.53, and on the Angoumois grain moth (*Sitotroga cerealella* Oliv.) - 0.43. *Trichogramma* activity in searching for main host eggs has been 2 times higher after rearing it on *Mamestra brassicae* than on unusual hosts (Table 2).

We consider that the problem can be effectively solved by replacing the Angoumois grain moth either by natural hosts or by artificial nutritional substrates. Wide introduction into practice of the commercial technology for *Trichogramma* rearing induces improvement of the entomophage survivability on the given laboratory host. There are 750 mechanized production lines functioning in the former U.S.S.R. which supply *Trichogramma* for 8-9 million ha (Abashkin et al. 1988). Research and production experience accumulated in our country formulates the scheme for a year cycle of *Trichogramma* rearing based on the collection of natural host eggs colonized by *Trichogramma* (at least 1,000-2,000) and the completion of 2 reproductions on natural host eggs and not less than 7 on the eggs of *Sitotroga cerealella* before releasing into the field.

Guaranteed collection of a great quantity of *Trichogramma* starting culture in nature can be provided by organizing nurseries -- places of artificial concentration of *Trichogramma* under natural conditions. Nurseries are crop conveyers where phytophage and entomophage monitoring is done during vegetation period. It considerably improves creation of a colony founder, one of the main lines in the scheme of *Trichogramma* rearing. Interpopulation crossings are one of the possible ways to increase the heterogeneity level of nursery material under mass production. Gene exchange between populations prevents their degeneracy and promotes quick adaptation changeability (Rusnak and Greenberg 1982; Greenberg et al. 1984; Greenberg, Rusnak, Djurich et al. 1986; Greenberg and Gavrilitsa 1989). The scheme proposed provides stable production of the second class *Trichogramma* ($D = 0.6-0.7$) with 60-80% biological effectiveness under optimal hygrothermal conditions during parasite release into the field. Republic or regional biolaboratories in the former U.S.S.R. are responsible for the production of natural host eggs and rearing of *Trichogramma* on them, i.e. for the preparation of the founding culture. Regional or collective farm

biolaboratories similarly existing in the former U.S.S.R. net of pedigree and seed farming are responsible for commercial production of *Trichogramma*.

Species competition gains importance under mass production and field release of *Trichogramma*. We have revealed mechanisms of competition between *T. evanescens* and *T. pinto* under laboratory and field conditions and ways to regulate it (Greenberg and Gavrilitsa 1983, Greenberg et al. 1984).

Techniques, regimes and equipment have been developed for long term storage (up to 7-8 months) of diapausing *Trichogramma*, its reactivation and for short-term storage (up to 30 days) of active *Trichogramma* (Shlyakhtich et al. 1989).

Recommendations have been prepared on long term storage of *Sitotroga cerealella* eggs in liquid nitrogen as well as sterile noctuid eggs (Gennadiev et al. 1985, Degtyarev and Yanishevskaya 1986). Scientifically grounded technology for *Trichogramma* application must take into account parasitoid behavioral peculiarities. It was established on the basis of observations and experiments that the laboratory population of *Trichogramma* has weak searching and migrational capacities. The parasite is searching for its host without any system. It finds and attacks the egg only at the distance of 1.5-10 mm. *Trichogramma* movements are occasional and are not associated with host distribution. Entomophage searching area is inversely proportional while frequency of occurrence with the host and biological effectiveness are directly proportional to cluster densities of pest eggs. Low host density reduces *Trichogramma* reproduction tempos. Parasite overcrowding increases intraspecific competition and mortality. Relationships of *Trichogramma* and *Ostrinia nubilalis* can serve as an example. Searching area of female parasitoids is 2.8 times higher at parasite-host ratio = 1:1 than at that of 11:1 (constituting 1,150 and 415 sq m respectively). The frequency of occurrence of the parasitoid with the host (parasite-host ratio = 1:1) at 2.5 egg clusters/100 plants is 9 times less than at 13 100 plants (the quantity of eggs parasitized constituting 33.1% and 68.4%, respectively). *Trichogramma* mortality at 13 egg clusters of *Ostrinia nubilalis*/100 plants is 4 times higher at parasite-host ratio = 11:1 than at that equal to 1:1. Moderate competition (parasite-host ratio = 11:1 or 6:1) regulates the population number maintaining it at about the same level (Greenberg and Boubetrin 1988). *Trichogramma* searching activity is

determined by endogenic and exogenic factors. The parasitoid is stimulated to host searching by the presence of eggs in the female ovariole and by the physiological age of host eggs. We noticed that under laboratory conditions *T. evanescens* parasitized 80-85% of 1-2 day old eggs of *Mamestra brassicae*, 40-50% of 3 day old eggs and 10-15% of 4 day old ones (Greenberg 1983). Abstention from oviposition results in the decrease of *Trichogramma* fecundity and reduction of the rate of their moving on the substrate (according to our data from 46.8 to 16.9 eggs/female and from 0.38-0.43 to 0.16-0.20 cm/sec. respectively). Leaf surface area and distance between plants greatly influence the rate and degree of host eggs infestation. For example, corn leaf biomass (for the period of *Trichogramma* release) increases from 13.5 to 26.0 thousands of square meters/ha and cabbage - from 16.9 to 54.2 thousands of square meters/ha. Total plant quantity/ha varies respectively from 50 to 70 and from 40 to 60 thousands. There was feedback between the variables mentioned.

Experiments demonstrated that the radius of *Trichogramma* effective activity when it moves independently constitutes about five meters, while when it is passive (with the wind) these distances can reach in average 10-15 m. Useful activity of adult *Trichogramma* from laboratory population is limited by 3-5 days.

One of the reasons of unstable entomophage effectiveness is pest distribution in time and space. Pests against which *Trichogramma* are used, as a rule, lay eggs evenly in the field while the parasitoid is mainly released into foci (50-100 points/ga). Flight and oviposition of Noctuidae, Pieridae and Tortricidae goes on continuously during 30-35 days of the first generation and up to two months of the second one. The parasitoid is released three times for this period. The number of releases depends on entomophage reproduction in nature. The population biotic potential and its growth rate directly relate to abiotic environment conditions and pest density. The role of daughter progenies of *Trichogramma* released into the field is manifested by the end of phytophage oviposition. According to our observations, the number of parasitized eggs varies from 60% to 100% which constitutes 10-15% of the total number of eggs killed by *Trichogramma* for one generation. One can correct release rates (Greenberg et al. 1989) only on the basis of models of dependence of fecundity, number of females and *Trichogramma* survival on abiotic and biotic factors. Thus, the scheme leaves time and space

when there's almost no danger for normal development of pests embryos. According to literary data, entomophage release rates vary from 20,000 to 600,000 parasitoid/ha and often don't agree with the density of pest egg clusters and parasitoid ecology. However, scientifically grounded *Trichogramma* release rates can be developed only taking into account density of phytophage egg clusters, quality of released *Trichogramma*, climatic conditions during parasitoid application and plant state. We developed mathematical models relating forecasted effectiveness of *Trichogramma* application with the above mentioned factors using as examples *Mamestra brassicae* on cabbage, *Ostrinia nubilalis* on corn, and *Lobesia botrana* (Den. et Schiff.) on grapes, with graphical and mechanical nomograms on the base of which one can calculate optimal parasitoid release rate. Once pest threshold number is reached, *Trichogramma* releases begin. Subsequent releases must be done every 5-6 days during the whole period of pest egg laying. Table 3 presents release rates of the 2nd class entomophage ($D=0.5-0.7$) under optimal hygrothermal conditions during release and average leaf surface of plants.

Guideline have been confirmed for the distribution of different aged *Trichogramma* which provide reliable effectiveness and a reduction of the number of releases from 5-6 to 2-3 (Greenberg et al. 1983). Traps baited with pest pheromones are used to establish optimal time and rates for *Trichogramma* release. The short term forecast of ovipositional intensities has been developed on the basis of average quantity of males caught per one trap for 5 days and biological peculiarities of *Ostrinia nubilalis* and *Mamestra brassicae* (Methodicheskie ukazania 1985). Comparison of forecasted and factual data on egg quantity shows correlation (r) at the level of 0.75-0.80. In the former U.S.S.R., adult *Trichogramma* are distributed by hand (100-200 points/ha) and eggs by mechanized devices 12 or 24 hours before adult emergence. At present some research institutions of the country developed and introduced technical means for ground and plane dispersal of *Trichogramma* (Recomendatsii po primeneniiyu trichogrammi v SSSR 1985).

Effectiveness of *Trichogramma* application is determined by the number of eggs parasitized. The higher the index is the better the effect of the procedure. However, it is not legitimate in our opinion. For example, *Ostrinia nubilalis* density equal to 4 egg clusters/100 plants is enough to get *Trichogramma* effectiveness in the range of 30% (taking

into account natural mortality of pest eggs) and bring its number to the threshold, 55% at 6 eggs clusters. At the same time, when *Ostrinia nubilalis* density constitutes more than 11 egg clusters/100 plants, even the effectiveness at the level of 70% doesn't provide density reduction to the threshold. Other target pests are characterized by a similar picture. A different approach to the evaluation of the effectiveness of *Trichogramma* and other plant protection means is sought to develop an application strategy that won't violate existing relationships between pests and beneficial organisms in agricultural biocenoses. The All-Union Institute of Biological Methods in Plant Protection - AUIBMPP) is developing a united criterion of *Trichogramma* effectiveness against *Ostrinia nubilalis*, *Mamestra brassicae* and *Lobesia botrana*. This criterion establishes biological and economic effectiveness of the entomophage.

Scientific and production experience shows that the greatest effectiveness can be achieved when *Trichogramma* is used in combination with other protection procedures. This includes the combination of multiple *Trichogramma* releases with rational use of pesticides, microbiological preparations, and an increased role of natural beneficial organisms. Great importance ought to be given to the development of the agrotechnical phone promoting increase of the effect of both chemical and biological techniques. Thus, timely and qualitative soil treatment permits 5-6 times reduction of cutting noctuid larvae, 30-40% reduction of *Mamestra brassicae*, *Plutella maculipennis* and *Pieris* sp. pupae, 40-50% reduction of *Loxostege sticticalis* pupae, and up to 80% reduction of diapausing pupae of *Laspeyresia nigricana*. Low cutting of corn (up to 10 cm from soil surface) followed by burning of plant remnants reduces *Ostrinia nubilalis* density 8 times because the main mass of diapausing pest larvae (up to 77.6%) lives higher than this level. Crop rotation and space isolation of plants from the places of pest reservation, sowing time, density of planting, and use of mineral fertilizers influence pest number considerably (Greenberg et al. 1987). Table 4 shows the effect of the crop cultivation agrophone on *Trichogramma* effectiveness against *Ostrinia nubilalis* on corn.

Microbial preparations must be components of IPM. It was established by AUIBMPP, Ukrainian Institute of Plant Protection and Belorussian Institute of Plant Protection that microbiopreparations (dendrobacillin, VIRIN-KS, VIRIN-XS, VIRIN-OS) had no toxic effect on *Trichogramma* 24

hours after application. Table 5 presents biological effectiveness of mutual and separate use of *Trichogramma* and lepidocid against *Ostrinia nubilalis*. The use of lepidocid against this pest (first use at larvae emergence and subsequent ones in 10 days intervals at a concentration of 0.5%) permits 2 times reduction of the population density. However, the effectiveness of the biopreparation is lower than that of the parasitoid which is explained by short period (several hours) of exposed mode of life of *Ostrinia nubilalis* larvae. The most effective was the variant where *Trichogramma* was combined with lepidocid. The introduction of *Bracon*, *Chrysopa*, *Aphidoletes*, *Aleochara*, *Tribliographa* and others will widen the assortment of biocontrol means used in IPM on cotton, vegetables and cereals.

Sowing of nectariferous grasses in field margins improves the activity of natural entomophages and increases *Trichogramma* effectiveness. The most difficult combination is *Trichogramma* with chemical plant protection means due to the fact that *Trichogramma* is characterized by having the least resistance to pesticides. It was established by AUIBMPP and AUIPP that the egg and larva stages of *Trichogramma* are more resistant to pesticides at concentrations close to commercial (but not ovicides). Susceptibility increases at the stage of pupae and especially at the stage of adults. Acaricides and aphicides pose considerable selectivity for *Trichogramma*. Lethal doses of the majority of broad spectrum insecticides are much less than those applied. Captan and cineb are the only fungicides selective for *Trichogramma*, others induce 50-100% mortality. It was established by the All-Union Institute of Plant Protection that methylmercaptafos, syfos, tedion, captan, cineb, and benlate can be referred to as pesticides with low persistence; rogor, phosolon, metafos, chlorofos, keltan, and uzgen have moderate ones. The rest have high residual toxicity for *Trichogramma*. When *Trichogramma* is applied in combination with chemicals, it is advised that broad spectrum insecticides with high initial and residual toxicity be excluded giving preference to selective or low persistent compounds. Chemicals ought to be used at least 3-4 days after parasitoid release. *Trichogramma* dispersal immediately after chemical treatments reduces the effectiveness of the procedure. It is necessary to take into account the duration of pesticide toxic effect.

In conclusion I'd like to mention that 5-12 g of *Sitotroga cerealella* eggs and 3-5 g of *Trichogramma* are produced from 1 kg of grains. The cost of 1 g of *Sitotroga cerealella*

eggs (50,000 eggs) constitutes 0.49 roubles, and 1 g of *Trichogramma* (80,000 eggs) costs 0.85 rouble. Total expenditures for *Trichogramma* application (field, vegetable crops, etc.) varies from 2.0 to 2.6 roubles/ha.

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Table 1. Biological effectiveness of *Trichogramma* depending on the quality of the biomaterial used

Intervals of values of united quality criterion (D)	Classes according to the quality	Forecasted biological effectiveness of <i>Trichogramma</i> (E)%
0.7 - 1.0	1	> 80
0.5 - 0.7	2	60 - 80
0.3 - 0.5	3	33 - 60
0.0 - 0.3	nonstandard	< 33

$$E = -0.527 + 112.99 \cdot D$$

Table 2. Comparative evaluation of the quality of *Trichogramma* reared on different hosts

Indices	Symbols	<i>Trichogramma</i> hosts		
		<i>Mamestra brassicae</i>	<i>Ephesia kuehniella</i>	<i>Sitotroga cerealella</i>
Emerged individuals (%)	a1	97.0	91.2	86.8
Number of females (%)	a2	62.1	57.0	52.2
Fecundity (individuals/female)	Π	116.5	74.6	59.4
Statistical quality criterion (a1/100 · a2/100 · Π)	y1	70.2	38.8	26.9
Activity for searching host eggs (%)	y2	55.5	26.9	20.4
United quality criterion	Д	0.96	0.63	0.43

Table 3. Release rates of *Trichogramma* against lepidopterous pests

Pest	Crop	Pest threshold	Pest density	Ratio 11:X (<i>Trichogramma</i> females:pest eggs)
Cutting noctuids	Sugar beet, Perennial grasses, Full fallow	0.4-0.6 individuals/m ²	1st release - 20,000 females/ha Subsequent releases: 0.7 - 4 ind./m ² 4.1 - 10 ind./m ² 10.1 - 15 ind./m ² > 15 ind./m ²	1:1 1:3 1:5 1:10
Leaf chewing noctuids with group egg clusters	Vegetables Sugar beet	4-5 eggs/m ² at 1st pest generation, 7-8 eggs/m ² at 2nd pest generation	1st release - 25-30,000 females/ha Subsequent releases: up to 10 ind./m ² 10.1 - 20 ind./m ² 20.1 - 50 ind./m ² > 50 ind./m ²	1:1 1:5 1:10 1:20
Leaf chewing noctuids w/ single egg clusters	Cotton, Tomato, Corn		up to 20 eggs/100 plants over 20 eggs/100 plant	70-75,000 females/ha 60,000 females/ha
<i>Ostrinia nubilalis</i>	Corn	2 ovipositions/ 100 plants	up to 6 egg clusters/100 plants 6.1-10 egg clusters/100 plants over 10 egg clusters/100 plants	5:1 1:1 1:2
<i>Loxostege sticticalis</i>	Agrocenoses with the pest	10-15 eggs/m ²	15-20 eggs/m ² 21-40 eggs/m ² 41-50 eggs/m ²	55,000 females/ha 50,000 females/ha 45,000 females/ha
<i>Pieris</i> sp.	Vegetable	10 eggs/m ²	1st release - 20,000 females/ha Subsequent releases: ----	1:10

Table 4. Survival of *Ostrinia nubilalis* under low and high agrophone of corn cultivation using *Trichogramma* (per 100 m²)

Index	Low agrophone				
	Mortality of the preceding stage individuals		Number of live individuals	log nos. live individuals	Mortality (K)
	number	%			
Diapausing larvae after overwintering 1984/85	2.0	15.4	13.0	1.10	0.06 (K1)
Pupated	2.0	18.2	11.0	1.04	0.09 (K2)
Adults emerged			9.0	0.95	
Eggs laid	1477.0	83.0	1780.0	3.25	0.77 (K3)
Larvae emerged	63.0	20.8	303.0	2.48	0.10 (K4)
Active larvae	216.0	9.0	240.0	2.38	1.00 (K5)
Larvae diapausing in plant remnants			24.0	1.38	K=2.02 F=2.17

Index	High agrophone				
	Mortality of the preceding stage individuals		Number of live individuals	log nos. live individuals	Mortality (K)
	number	%			
Diapausing larvae after overwintering 1984/85	2.1	20.8	10.1	1.00	0.10 (K1)
Pupated	2.0	25.0	8.0	0.90	0.12 (K2)
Adults emerged			6.0	0.78	
Eggs laid	1257.0	83.5	1506.0	3.18	0.78 (K3)
Larvae emerged	50.0	20.1	249.0	2.40	0.10 (K4)
Active larvae	192.7	96.8	199.0	2.30	1.50 (K5)
Larvae diapausing in plant remnants			6.3	0.80	K=2.60 F=2.17

Table 5. Effectiveness of means for biocontrol of *Ostrinia nubilalis* Hbn.

Variants	% damaged plants	Intensity of damage	Number larvae/damaged plant	Population density larvae/m ²
Standard	72.0	54.5	2.0	7.20
<i>Trichogramma</i>	33.0	16.3	0.8	1.32
Lepidocid	53.0	22.3	1.2	3.18
<i>Trichogramma</i> + lepidocid	25.0	11.4	0.5	0.62

Propagation and Release of Natural Enemies for Control of Cotton Insect and Mite Pests in the United States, including Status and Prospects for using *Microplitis croceipes*

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Introduction

The aggregate damage attributed to insect and mite pests in United States cotton ranged from 7 to 14 percent, annually, during the last decade (Suguiyama and Osteen 1988). These losses occurred in spite of the best control efforts. In 1989, arthropod pests reduced cotton yields by 9.2 percent in the United States, resulting in a loss of 1.1 million bales from potential yield and \$319 million in revenue. Additionally, the cost for insecticides and miticides to control the pests was \$366 million. The total cost of arthropod pests to United States cotton production in 1989 was \$685 million (King and Herzog 1990).

Biological Control Drivers

Obviously, the cost of yield losses coupled with the cost of control drastically reduces the profitability of producing cotton in the United States. Nevertheless, United States cotton producers have and still are relying heavily on synthetic pesticides to control arthropod pests (Herzog and King 1990). These chemicals are relatively fast-acting, often control a complex of pests, can be used at a grower's discretion on a field-by-field basis, and generally are cost effective as compared to alternative control methodologies.

Nevertheless, the availability of effective pesticides is declining precipitously. On the one hand, many pesticides have been rendered obsolete because of resistance buildup beginning with the organochlorines, followed by the organophosphate and carbamate compounds, and most recently the pyrethroids. On the other hand, the United States public has become more and more alarmed about the safety of their food and water as well as impact of pesticide residues on animal and plant life threatened by extinction (King et al. 1988). Consequently, many chemicals have been banned from usage. Moreover, use of pesticides is being restricted by The Endangered Species Act of 1973, which requires the Environmental Protection

Agency (EPA) to protect endangered and threatened species under the Federal Insecticide, Fungicide, and Rodenticide Act.

These public concerns, coupled with the cost of searching for new, effective compounds have escalated the cost of registering new chemicals. The cost of acquiring the first label for registered use of a single pesticide has been estimated at \$20 to 50 million. Many chemicals registered prior to November 1984 are not being re-registered under EPA requirements because of putative chronic health effects and ground water leaching.

Finally, synthetic pesticides are petroleum based, and this non-renewable resource is becoming less plentiful and more expensive. The effects of synthetic pesticides on natural enemy populations with consequent elevation of secondary pests to primary pest status, previously innocuous arthropods to pest status, and pest resurgence are discussed in subsequent sections of this paper.

There is renewed interest in the United States in the development of non-chemical methods for controlling arthropod pests. Certainly, biological control must receive high priority. Biological control involves managing natural enemies and their products to reduce pest populations and their effects. (Natural enemies refers to predators, parasitoids, and pathogens, but in this paper the term is restricted to predators and parasitoids.) Interrelated strategies are conservation, importation, and augmentation. Conservation is preservation of indigenous natural enemies. Classical biocontrol involves importation for release and establishment where natural enemies are lacking. Augmentation is propagation and release of natural enemies in selected areas where natural enemies occur in too few numbers.

Integrated Pest Management

Biological control is an integral component of the cotton integrated pest management strategy in the United States (King 1986). Integrated Pest Management (IPM) has been defined as a system in which all available techniques are evaluated and consolidated into a unified program for managing pest populations to avoid economic damage and minimize adverse side effects on the environment (NAS 1969). For example, with regard to controlling the bollworm, *Helicoverpa* (= *Heliothis*) *zea* (Boddie) and the tobacco budworm, *Heliothis virescens* (F.), United States

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cotton-insect control guides often provide a list of the predators that may be encountered while surveying insect pest infestations. Parasitoids (parasites in the class Insecta) are usually mentioned, but not by name. Often these guides provide illustrations of important natural enemies. Typically, efforts are made to spare natural enemies by restricting insecticide applications thereby maximizing pest suppression action (King 1986).

Avoidance of pesticide usage has often been cited as precluding the buildup of pest populations such as bollworm and tobacco budworm, aphids, whiteflies, and mites because of pesticide-related mortality to the natural enemies (Bottrell and Adkisson 1977). A particularly outstanding book outlining the IPM strategy for managing cotton pest populations is "Integrated Pest Management for Cotton in the Western Region of the United States" (Anonymous 1984).

Unfortunately, natural enemy populations often occur in too few numbers to prevent the buildup of pest arthropod populations to damaging levels. Certain pests such as the boll weevil, *Anthonomus grandis grandis* Boheman, plant bugs such as *Lygus* spp., the cotton fleahopper, *Pseudatomoscelis seriatus* (Reuter), and the pink bollworm, *Pectinophora gossypiella* (Saunders), generally do not have effective natural enemies in cotton fields. Efforts have been made to import and establish effective natural enemies of these pests (boll weevil - Cate 1985; plant bugs - Coulson 1987; pink bollworm - Clausen 1978 and Legner 1979) as well as the bollworm and tobacco budworm (Powell 1989), but these efforts have been unsuccessful. E. F. Knipling (1979, Unpubl. Data) has developed numerous theoretical models demonstrating the technical feasibility of controlling pest populations by augmenting predator or parasitoid populations. Knipling (personal communication, 4 April 1990) conceptualized his thesis for augmentation as follows: "Host dependent parasites have evolved systems allowing reproduction without jeopardizing existence of the host. The coexistence patterns, in numerical terms, operate within rather narrow limits. However, addition of the parasites in sufficient numbers at strategic times can result in virtual elimination of the host."

The technical feasibility of propagating and releasing parasitoids and predators to control arthropods has been demonstrated repeatedly. This subject has been reviewed extensively (DeBach and Hagen 1964, Ridgway and Vinson

1977, King et al. 1984, King et al. 1985a, King et al. 1985c). Van Lenteren (1986) reviewed the augmentative releases of parasitoids in greenhouses. Greany et al. (1984) briefly review the potential for using semiochemicals to manipulate parasitoids and the need for artificial culture techniques to mass propagate them. In general, the use of predators and parasitoids to control cotton pests was included in these reviews, but no review was devoted exclusively to this topic. Thus, the following discussion will focus on state-of-the-art control of four primary pests or pest complexes in the United States by augmentative releases of predators and parasitoids: bollworm/tobacco budworm complex; the boll weevil; the pink bollworm; and plant bugs, specifically *Lygus* spp.

Control of the Bollworm and Tobacco Budworm

Parasitoids

The principal parasitoids that contribute to mortality of bollworm and tobacco budworm eggs and larvae are given in the following list.

Important parasitoids and predators of *H. zea* and *H. virescens*

Parasitoids	Predators
<i>Microplitis croceipes</i>	<i>Geocoris</i> spp.
<i>Cardiochiles nigriceps</i>	<i>Orius</i> spp.
<i>Cotesia marginiventris</i>	<i>Chrysoperla</i> spp.
<i>Campoletis sonorensis</i>	Coccinellids
<i>Trichogramma</i> spp.	Nabids
<i>Eucelatoria bryani</i>	Spiders

Of these parasitoids, primary attention has been given to augmenting *Trichogramma* populations. More recently, major emphasis is being placed by three Agricultural Research Service (ARS) laboratories on the development of augmentative technology for the larval endoparasitoid *Microplitis croceipes* (Cresson). One laboratory also is researching the use of the tachinid, *Archytas marmoratus*

(Townsend), and considerable progress at another laboratory has been made on the *in vitro* rearing of the tachinids, *Eucelatoria bryani* Sabrosky and *Pallexorista laxa* (Curran).

Trichogramma

Biological control of the bollworm and tobacco budworm in cotton by augmentative releases of *Trichogramma* in the United States, particularly *T. pretiosum* Riley, is comprehensively reviewed in King et al. (1985a). All aspects are reviewed including rearing (Morrison 1985a, 1985b), transport, storage, and parasitoid release technology (Bouse and Morrison 1985), behavioral manipulation (Lewis et al. 1985) and parasitoid movement (Keller and Lewis 1985), efficacy (King et al. 1985b, Lopez and Morrison 1985), pesticide effects (Bull and Coleman 1985), and modeling of augmentative releases (Goodenough and Witz 1985). Another recent popularized review of the state-of-the-art technology for identifying, propagating, and augmenting *Trichogramma* populations is given by Olkowski and Zhang (1990).

Olkowski and Zhang (1990) list seven commercial producers of *Trichogramma* in the United States. These parasitoids are released over a total of about 81,000 hectares. The parasitoid most commonly reared and released in cotton is *T. pretiosum*, and the Angoumois grain moth, *Sitotroga cerealella* (Olivier), is the host of choice.

The technical feasibility of suppressing bollworm and tobacco budworm populations in cotton by augmentative releases of *Trichogramma* has been repeatedly demonstrated in the United States (Table 1). Lingren and Kim (unpublished data) manually released 494,000 adult *Trichogramma*/ha resulting in about 60% parasitism of bollworm and tobacco budworm for over a month in and near the release area. Aerial releases of 123,500-247,000 adult *Trichogramma*/ha resulted in an average 51% parasitism of bollworm and tobacco budworm eggs on five Texas cotton farms (Ridgway et al. 1977).

Stinner et al. (1974) evaluated the technical feasibility of reducing bollworm and tobacco budworm larval populations in cotton by releasing *T. pretiosum*. Parasitoid release rates were high (up to 957,000/ha), but larval populations were suppressed. King et al. (1985b) reported three years of data following releases of *T. pretiosum* in cotton. In each year, egg parasitism was increased as a consequence of the release of parasitoids, but these parasitism rates could not be correlated with larval suppression.

In the third year, parasitoid release plots yielded more cotton than untreated plots, though only 77% as much lint as in the insecticide-treated plots.

Perhaps the major factor limiting *Trichogramma* use for bollworm/tobacco budworm control in cotton in the United States is the preferential use of effective chemicals for controlling a complex of pests including plant bugs and the boll weevil. Since *Trichogramma* is extremely sensitive to nearly all synthetic chemicals, its use is prohibited. This situation may change as chemicals become less available, boll weevils are eliminated as a pest from parts of the United States, and other nonchemical control strategies are developed. More research is needed to develop technology for managing parasitoids after release and for producing more vigorous parasitoids with longer life spans. Current procedures call for releasing the parasitoid at rates exceeding 100,000/ha at 3-day intervals during moth oviposition periods.

Larval Parasitoids

Larval parasitoids are an important part of the environmental resistance to increase of bollworm and tobacco budworm populations. Unique complexes of hymenopterous and tachinid parasitoids have been recorded in the various regions of the world (King and Jackson 1989). Cumulative rates of larval parasitism are often high but the predominant species vary between regions of the country in the United States as well as crop (King et al. 1982). Special attention will be given to *M. croceipes*, one of the most important parasitoids of bollworm and tobacco budworm larvae in cotton and wild host plants in the United States (King and Powell 1989). Over 50% parasitism of larvae was recorded during 1981 and 1982 in a series of cotton fields in the midsouthern United States despite application of insecticides.

Potential for using larval parasitoids in augmentative releases has been indicated in small-scale tests. Lingren (1969) reported that *Cotesia* (= *Apanteles*) *marginiventris* (Cresson) had considerable potential for use in augmentative programs. Also, *Campoletis sonorensis* (Carlson) released at the rate of 680/day for 10 consecutive days in a 0.2-ha cage (34,000 wasps/ha equivalent) infested with tobacco budworm larvae resulted in 85 percent parasitization for nine consecutive weeks (Lingren 1977). Jackson et al. (1970) reported 58 percent parasitization of third-instar tobacco budworm larvae in cages when 2964 (equivalent) *M. croceipes* female wasps were released per hectare.

Jackson et al. (1970) reported that if the tachinids, *E. bryani* and *P. laxa*, were released at the rate of 6,175 female flies/ha on cotton containing 12,350 bollworm and tobacco budworm larvae/ha, about 50 percent parasitization should occur in two days.

Research on *M. croceipes* has been extensively reviewed (Powell et al. 1989). Basic biology including host relationship physiology was recently reviewed by Powell and Elzen (1989) and Vinson and Dahlman (1989). Behavioral aspects relating to habitat and host location, mate finding, and mating were reviewed by Nordlund et al. (1989), Elzen and Powell (1989), and Jones (1989). Other research vital to development of augmentative technology for *M. croceipes* is the effect of insecticides on the parasitoid (Bull et al. 1989), genetic characterization and genetic improvement (Steiner and Teig 1989), and the possibility of developing an *in vitro* rearing system for the parasitoid (Greany et al. 1989).

Hopper (1989) surmised that augmentation of *M. croceipes* for control of the bollworm and tobacco budworm is technically feasible. Of the principal parasitoids of the bollworm and tobacco budworm, across host plants, *M. croceipes* has emerged as one of the most important (King et al. 1985c, King and Powell 1989). King et al. (1985d) hypothesized, based on dramatically higher rates of bollworm and tobacco budworm larval parasitism, particularly by *M. croceipes*, that *M. croceipes* was highly tolerant of many commonly used insecticides, particularly the pyrethroids. In general, the parasitoids are more tolerant of certain pyrethroids (e.g., esfenvalerate and cypermethrin) and carbamates (e.g., thiodicarb and oxamyl) and least tolerant of certain organophosphates (e.g., acephate and profenofos) (Powell and Scott 1985).

Microplitis croceipes prefers to parasitize third instars (Hopper and King 1984b), but all parasitized instars move and feed less on the cotton plant (Hopper and King 1984a). Consequently, less damage is caused by parasitized larvae. Hopper et al. (1991) report that releasing 2,000 female *M. croceipes* per hectare of cotton resulted in 75 % parasitized bollworm and tobacco budworm larvae after six days, with an estimated 38 % reduction in damage. Hopper (1989) suggested that releases over large areas, particularly during

the time that bollworm and tobacco budworm are restricted to wild host plants (valid only for the Midsouth United States), might be an effective population suppression tactic.

Growers may not use *M. croceipes* in cotton even if it could be mass produced because apparently the presence of feeding larvae in cotton would not be tolerated, though feeding is reduced. Perhaps the best approach would be releasing parasitoids on an area-wide basis while bollworm/tobacco budworm populations are still on early-season wild host plants along roadsides and field margins, as stated in this proceedings by D. D. Hardee. This area-wide suppression would provide an additive mortality factor to virus application, and parasitoids would search where the virus had not been applied.

Predators

No predators are currently being propagated and released for controlling the bollworm and tobacco budworm in cotton in the United States. Most management models do include predator-caused mortality, at least indirectly if not directly (See T. R. Wagner, these proceedings).

Releases of several hemipteran predators indicate that it might be feasible to augment their populations if economical procedures for mass producing them could be developed. Field-cage studies by Lingren et al. (1968), van den Bosch et al. (1969), and Lopez et al. (1976) with *Geocoris punctipes* (Say), *Nabis americoferus* Carayon, and *Podisus maculiventris* Say, respectively, in cotton demonstrate their ability to suppress bollworm and tobacco budworm populations.

Ridgway and coworkers demonstrated the technical feasibility of suppressing bollworm and tobacco budworm larval populations in cotton by periodic release of *C. carnea* eggs or larvae (Table 2). Release of 2- to 3-day-old larvae consistently produced significant reductions of bollworm and tobacco budworm populations on cotton. Reductions in bollworm and tobacco budworm larval populations were obtained by releasing as few as 24.7 thousand *C. carnea* larvae/ha, and high levels of reduction were obtained in the field by releasing 247,000 to 494,000/ha (Ridgway et al. 1977).

Control of the Boll Weevil

Successful colonization of cotton, a new host plant, enabled the boll weevil to migrate from its original distribution area in southeastern Mexico and north-central South America to the United States through the wild and cultivated cottons of Mexico (Burke et al. 1986). The boll weevil escaped its effective natural enemies, and attempts to establish effective species on it have failed so far.

At least 55 indigenous parasitoid species are known to attack the boll weevil in the United States (Pierce 1908, Hunter 1910, Pierce et al. 1912, and Chestnut and Cross 1971). These parasitoids characteristically have a wide host range and are facultative parasitoids of the boll weevil (Pierce 1908, Cushman 1911). Consequently, they do not respond to boll weevil population dynamics as would a more host-specific parasitoid. One of these parasitoids, *Bracon mellitor* Say, has been studied (Adams et al. 1969, Barfield et al. 1977), and is often recorded from field-collected, weevil-infested fruit (Bottrell 1976). *Bracon mellitor* parasitism rates of the boll weevil can be high (Marlatt 1933), and these rates are affected by cotton variety (McGovern and Cross 1976, Adams et al. 1969). However its facultative host selection behavior, failure to search the ground for weevil larvae, and preference for late instar larvae reduces its effectiveness (Cate 1985, Meinke and Slosser 1982).

Cate and associates have identified at least 14 parasitoids attacking the boll weevil and a closely related species, *Anthonomus hunteri* Burke and Cate, in southern Mexico. Rearing techniques have been developed for several of these species (Cate 1987).

One of the most promising exotic species is the pteromalid *Catolaccus grandis* Burks. Cate (1985) reported that experimental field releases of *C. grandis* in Mississippi resulted in a five-fold population increase in larval parasitism, but the parasitoid failed to survive the winter. In a south Texas study, low rates of *C. grandis* released on low density host populations resulted in high parasitization rates (Morales-Ramos and King, 1991). Certainly, indications are that *C. grandis* is an efficient host searcher and it is capable of parasitizing a high percentage of boll weevil-infested fruit. So, its failure to overwinter can be overcome by annual propagation and release. Knipling (1990, personal communication) demonstrated in a simulation model that release of as few as 20 female *C. grandis* per

acre of cotton could result in high rates of parasitism and virtual elimination of damage from progeny of F_1 generation adult weevils. Successful nonchemical control of this key pest might allow successful biological control of bollworm, tobacco budworm and other secondary pest populations.

Control of the Pink Bollworm

Several native predators and exotic parasitoids have been evaluated as potential candidates for augmentation against pink bollworm. Studies by Irwin et al. (1974) suggested that most predators tend to be effective against the pink bollworm only at relatively high densities. Strategies have been developed to manipulate certain crops as field "nurseries" for native predators, e.g., alfalfa (Stern et al. 1967) and sorghum (Fye 1971, DeLoach and Peters 1972, Fye and Carranza 1972, Robinson et al. 1972).

Bryan et al. (1973a, 1973b) released more than two million *Bracon kirkpatricki* and ca. 280,000 *Chelonus blackburni* in approximately 113 acres (46 ha) of Arizona cotton during 1972, and documented a significant reduction in the need for insecticidal treatment in release plots (one treatment for *Lygus* and one for pink bollworm) versus control plots (four treatments for pink bollworm and one for the bollworm). Parasitism by *B. kirkpatricki* ranged up to 25 percent (which the authors considered an underestimation), whereas *C. blackburni* appeared to be largely ineffective (which the authors attributed to release in insufficient numbers). Later, Bryan et al. (1976) documented parasitism of about 32 percent by *B. kirkpatricki* and about nine percent by *C. blackburni*, but concluded that such rates were insufficient to control pink bollworm.

Inundative release of several parasitoid species in the lower Colorado Desert of Arizona and California produced variable levels of pink bollworm control (Legner and Medved 1979). Most effective was *Chelonus* sp. nr. *curvimaculatus* Cameron, which was credited with an adjusted 69.6 percent infested boll reduction at the equivalent release rate of 2,667 females/ha (Legner and Medved 1979). The prospects of parasitoid augmentation as an effective control strategy have been enhanced by the fact that artificial diets and/or mass-rearing procedures have been developed for pink bollworm (Adkisson et al. 1960, Stewart 1984) and several of its associated hymenopterous parasitoids (Bryan et al. 1969).

Control of *Lygus* Species

Lygus are attacked by a wide range of predators and parasitoids, particularly while on host plants other than cotton. A particularly effective predator of plant bugs is *Geocoris* spp. (Leigh and Gonzalez (1976). High rates of egg parasitism (36 percent) by the mymarid, *Anaphes iole* (Girault) (= *A. oviventris* (Crosby and Leonard)) has been recorded in cotton (Graham et al. 1986), but most studies indicate highest rates of parasitism in agriculturally undisturbed areas (Scales 1973, Sillings and Broersma 1974).

Debolt (1987) discusses in some detail the potential for using augmentative releases of parasitoids to control *Lygus*. The development of an artificial diet for *L. hesperus* (Debolt 1982) has made the production of large numbers of host *Lygus* nymphs and eggs possible. An ARS Pilot Test is presently being conducted to assess the technical feasibility of controlling *L. hesperus* in alfalfa by augmentative releases of the mymarid egg parasitoid, *Anaphes iole*, the braconid nymphal parasitoid *Leiophron uniformis* (Gahan). Control of *L. hesperus* in alfalfa would limit migration of the bugs into cotton after the plant is cut for hay or matures for seed production.

In small field plots in 1990, average egg parasitism rates of 57% were achieved with *A. iole* with single releases of 130,000 parasitoids (male and female) per acre. Average parasitism levels of 29% of the nymphs occurred following one-time releases of 22,000 female *L. uniformis* per acre (C. G. Jackson, Personal communication, 23 August 1990).

Insect Rearing

Efficient and cost effective methods of rearing predators and parasitoids must be developed if augmentative releases are to be feasible (Beirne 1974). Literally millions of natural enemies, available at somewhat unpredictable times, may be required for commercial augmentative releases. Finney and Fisher (1964) discussed problems associated with the culture of predators and parasitoids. Considerable attention has been devoted to development of techniques to produce quality insects in large numbers (King and Leppla 1984, Smith 1966). The genetic implications of long term laboratory rearing of insects are addressed elsewhere (Bouletreau 1986, Mackauer 1972, 1976).

Powell and Hartley (1987) described techniques for manually producing large numbers of parasitoids efficiently. These authors adapted a multicellular host rearing tray technique (Hartley et al. 1982) to rear *M. croceipes* and several other species of parasitoids. Techniques, involving use of low temperature storage, allowed simultaneous release of nearly 17,000 wasps. They noted several factors that were important for maintaining the rearing program which may be applicable to others. The quality of mass-reared insects also should be assessed (Boller and Chambers 1977).

Our present inability to mass propagate parasitoids and predators of assured quality for a competitive cost is a major constraint to the augmentative approach in the United States. However, this may not pose a challenge in the near future as scientists (J. L. Roberson, D. D. Hardee) at the USDA Gast Rearing Laboratory, Southern Insect Management Laboratory, come closer to making automated mass production of *M. croceipes* a reality (Powell and Roberson, In press). Commercialization may be practical only for selected organisms for which suitable diets and storage methods are developed. Artificial rearing is the "break-through" that would potentiate practical use of augmentation for widespread pest control. Various groups have made progress in *in vitro* rearing of parasitoids, but a feasible system remains to be developed. As many as 22 entomophagous species have been reared *in vitro*. Several Hymenoptera (1 ectoparasite, 4 pupal parasitoid species, 4 species of *Trichogramma*) and 3 species of Diptera have been cultured with varying success (King et al. 1984). Predators, notably *C. carnea*, have been reared on artificial diets (Vanderzant 1973, Martin et al. 1978).

While there have been numerous successes in oviposition stimulant identification or partial rearing (Nettles and Burks 1975, Nettles 1982), definitive development of a feasible *in vitro* rearing system for parasitoids has yet to be developed. Although considerable advances have been made in *in vivo* rearing, the advances have not been achieved to such an extent with *in vitro* rearing. The recent work of Wu et al. (1982) illustrated an instance in which a completely synthetic artificial host egg was produced which contains no insect derivatives, and supports *Trichogramma* oviposition and development.

Hymenopterous larval endoparasitoids have not been successfully reared to the adult stage on artificial diet. However, *C. marginiventris* and *M. croceipes* have been

reared on artificial media through the first instar (P. Greany, pers. com.). Larval endoparasitoids have evolved complex mechanisms that interact with the host's internal dynamics and organs without damaging this environment or causing untimely demise of the host. The workings of these interacting factors must be at least understood minimally for *in vitro* rearing of larval endoparasitoids to become a reality (Thompson, 1986).

Developments in rearing natural enemies on artificial diet may allow us to produce sufficient numbers to further evaluate natural enemies as biological control agents. An artificial diet that can be encapsulated has been developed for *Chrysopa*, and *G. punctipes* has been reared for more than 65 generations on an artificial diet (Cohen, In Press). In both cases, mass propagation requires significant engineering input.

Behavioral Manipulation

A variety of behavior-modifying chemicals (semiochemicals) affect the actions of predators and parasitoids in cotton and surrounding fields. These chemicals function at different trophic levels. In addition to chemicals from the parasitoid or predator and from the host or prey, chemical cues emanating from the host habitat affect the behavior of the natural enemies. Moreover, chemical cues from the parasitoid or predator may be used in host seeking by hyperparasitoids.

Understanding this complex chemical communication by parasitoids and predators, and between the different trophic levels, is critical for managing natural enemies and predicting levels of biological control.

Numerous kairomonal relationships between cotton arthropod pests and their natural enemies have been reported. For example, dispersal from the target area after augmentative release of predators or parasitoids often reduces the effectiveness of the augmentative approach. Provision of supplemental resources such as kairomones to attract, arrest, retain, or stimulate the natural enemy to search more intensively for the host or prey could provide mechanisms for managing parasitoids and predators (Nordlund and Sauls 1981). Tricosane and other hydrocarbons extracted from moth scales have been shown to increase parasitization by *Trichogramma* spp. (Gross et al. 1975, Jones et al. 1973). Oviposition stimulating kairomones have been extracted

from the accessory gland of the female bollworm (Nordlund et al. 1987). The sex pheromone, gossypure, from the pink bollworm caused increased parasitization of pink bollworm eggs by *T. pretiosum* (Zaki 1985). Kairomones have been extracted from the frass of bollworm and tobacco budworm larvae that cause host seeking by the larval parasitoids *M. croceipes* and *Cardiochiles nigriceps* Viereck; one chemical identified was 13-methylhentriacontane (Jones et al. 1971, Nordlund and Lewis 1985, Heath et al. 1990). A proteinaceous material found in the frass or hemolymph of tobacco budworm larvae stimulated larviposition by the tachinid *A. marmoratus* (Nettles and Burks 1975).

Other behavioral chemicals termed synomones because they facilitate location of the host by the parasitoid and consequently benefit the parasitoid and plant, have been found in cotton. The ichneumonid, *Camponotus sonorensis* Cameron was shown to orient to and search host-free cotton plants (Elzen et al. 1983). Host-searching behavior by *C. sonorensis* (Elzen et al. 1984) and *M. croceipes* (Nordlund and Sauls 1981) increased on artificial diet-fed bollworm and tobacco budworm larvae if cotton-plant material was put in the diet. Turlings et al. (1990) discovered terpenoid volatiles from corn plants after feeding by *Spodoptera exigua* (Hübner) caterpillars that attracted females of the parasitic wasp *Cotesia marginiventris* (Cresson) for host finding. They concluded that these terpenoids may be produced in defense against herbivores but may also serve a secondary function in attracting herbivore natural enemies.

Predators respond to many of the same chemical cues. Lewis et al. (1977) demonstrated an increased search rate by the common green lacewing, *Chrysoperla carnea* Stephens, on eggs of the bollworm when bollworm moth scales or extracts of the scales were applied to the search area. A compound in cotton, B-caryophyllene, was attractive to adult female green lacewings (Flint et al. 1979). Sabelis and Dicke (1985) summarized data showing that the phytoseiid mite, *Phytoseiulus persimilis* Athias-Henriotuses, uses kairomones from its prey to locate it.

Summary

Much of the basic information required to implement biological control by augmentation in the United States is available. Enhanced knowledge on management of predator and parasitoid behavior coupled with use of genetically

improved strains will lead to increased effectiveness of biological control. The development of artificial diets and *in vitro* rearing procedures for parasitoids and predators will open the path for their mass production and commercial distribution for augmentative releases. Over the next decade, social and environmental pressures in many countries will expedite implementation of technology for biological control of arthropod pests of cotton as well as other crops by propagation and augmentative releases of their natural enemies (predators and parasitoids).

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Table 1. Biological control of *H. zea* and *H. virescens* in cotton by augmentative releases of *Trichogramma*

Release Rate/ha (x 1,000)	% Parasitism	Control Evidence	Reference
46-957	33-81	66-80% larval reduction	Stinner et al. 1974
112-178	55-84	21% larval reduction	Jones et al. 1979
110	15-90	larval reduction	Ables et al. 1979
47	42-80	inadequate suppression	Luttrell et al. 1980
413	28-60	31% increased yield	King et al. 1985b

Table 2. Augmentative release of *Chrysoperla carnea* for biological control of *H. zea* and *H. virescens* in cotton fields

Release rate/ha (x 1,000)	% Larval reduction
494	82
227	89
25	33
74	54
247	83

(Ridgway, King and Carrillo 1977)

Integration of Techniques and Methods of Cotton Protection from Pests in Tajikistan

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Young cotton is infested by a complex of insect pests and mites which develop for 3-24 generations and feed on plants during the entire growing season until harvest. Potential losses (without control measures) can constitute 60% of the yield and prevent the need for cultivation. Hence, plant protection is an important component of cotton growing technology.

A historical review of cotton improvement systems reveals several stages. The first and most difficult stage was characterized by transition from total aerial treatments with insectoacaricides in 1950-1960 to mainly ground applications based on damage thresholds of phytophages. Treatment thresholds include 10-12 *Helicoverpa armigera* larvae/100 plants of average-staple cotton, 3-5 pests/100 plants of fine-staple cotton, 0.3-0.5 of *Agrotis segetum* larvae/1 m², 10% cotton infestation with aphids and 5% infestation with *Spodoptera exigu*a Hb.

Limited use of chemicals was also conditioned by necessity to reduce resistance of chewing pests to chlorinated hydrocarbons and sucking pests to organophosphates. By the end of 1960, pest resistance to these preparations became a serious problem: every treatment stimulated pest reproduction and killed natural enemies (parasitoids and predators) resulting in losses in yield. The use of new chemicals and their rotation according to damage thresholds reduced pesticide effect on plants. It decreased insecticide treatments 2.5 times and acaricide treatments 3.5 times from 1967 to 1976.

To strengthen this tendency, special attention was paid to non-chemical means of pest suppression. Cultural practices which either suppressed or stimulated development of noxious insects and mites have been evaluated. Regimes for fertilization and irrigation were found to play key roles in irrigation farming. Studies carried out in Guissar Valley revealed relationships of aphid number and the quantity of nitrogenous fertilizers applied. The use of 400-500 kg of fertilizers/ha (instead of recommended 200-250 kg/ga) allowed cotton aphid density to be maintained in the range of 800-4,000 aphids/plant. Three to four insecticidal treatments did not reduce the resistance development. Proper use of nitrogenous fertilizers and

elimination of weeds surrounding cotton fields maintained aphid density at the level of 47-296 pests/plant using only one chemical treatment.

Proper application of pesticides promotes reproduction and accumulation of natural enemies by stimulating development of natural insect populations. According to the data obtained by M. N. Narzikulov and Sh. A. Umarov (1961), 226 natural enemies including 192 parasites and predators (84%) were recorded in cotton agrobiocenoses. Each of them plays a certain role in phytophage management. Their total ability to protect cotton without chemicals was named by the authors as the level of entomophage effectiveness. To provide reliable pest control it is necessary to have 250-300 entomophages/100 cotton plants. These figures differ when dealing with different pests: e.g., 150-200 against *Helicoverpa armigera*, and *Tetranychus urticae* but only 100-150 against aphids.

Since predators and parasitoids regulate their numbers and developmental tempos depend on pest density. Low pest density can fail in attracting entomophages; a high one can result in yield loss. To guarantee the yield, we consider it reasonable to use the concept of "minimum necessary pest number." This is the ecological criterion reflecting the number of insect pests and mites needed to guarantee establishment and accumulation of natural entomophages. This pest number does not endanger the crop yield. For example, the first Coccinellidae were recorded on cotton after infestation by aphids of 5-7% of plants; mass flight - at 12-18% with the density of 10 and more aphids/leaf.

The following procedures increase activity of natural entomophages: minimum soil treatment, adherence to damage thresholds, strict focus on treatments with insectoacaricides (preferably of selective activity), and increased alfalfa acreage (especially for seeds). The latter is of special importance since alfalfa unplowed for 3 years and untreated with chemicals serves as a place for accumulation and overwintering of entomophages. Strip mowing improves ecological functions of this crop.

Artificial rearing and mass applications of entomophages are very important for intensive cotton growing and represent the second component of biocontrol which is based on the knowledge that:

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- multifactor mechanisms of agroecosystem self-regulation where (difficult for management) forces of nature predominate and are unreliable, and
- there is a necessity to change ratio of beneficial and noxious species by releasing laboratory reared parasitoids and predators.

In many cases, according to K. E. Voronin (1984), entomophages released together with other components regulate seasonal pest numbers and provide an ecological balance sooner than under natural conditions.

Trichogramma pinto and *Bracon hebetor* are used on cotton in conjunction with parameters developed at the Plant Protection Department of Tajik Institute of Plant Protection. They are produced by 31 biolaboratories of the republic and are released at an optimum rate of 60,000 *Trichogramma* females/ha at 20-25 *Helicoverpa armigera* eggs/100 plants assuming 50% hatch. Such a density corresponds to 10-12 larvae/100 plants which is permissible. On hatch of 60% or more larvae, 70,000-75,000 *Trichogramma* are released when 15 pest eggs/100 plants are found. Similar to natural entomophages, 15 *Helicoverpa armigera* eggs are considered the maximum necessary rate; complete dispersal of preimaginal stage guarantees success. One release of *Trichogramma* eliminates an average of 50% of host eggs. To provide control of egg laying of one generation of *Helicoverpa armigera*, "flood" with *Trichogramma* by releasing 3-4 times every 4-5 days.

Unlike *Trichogramma*, *Bracon* released into the field establishes itself quickly by feeding on flower pollen and preying on hemolymph: *Bracon* completes 2-5 generations during development of one *Helicoverpa armigera* generation. The optimal rate of 800-1,000 parasitoids/ha provides 80% mortality of *Helicoverpa armigera* larvae. *Bracon* is very susceptible to changes in host number; i.e., when plots vary in host density, the aggregate in areas where there are at least 5-7 larvae/100 plants; this host density is the signal for the parasitoid release.

Bracon effectiveness depends on several factors, including what crop borders cotton. Thus, if *Bracon* is released in a tomato field surrounded by cotton, the parasitoid remains on tomatoes, the more attractive crop, and the biocontrol effect on cotton is the biggest. If it is surrounded by

vineyards, blossoming corn or orchards, less migration from tomatoes occurs, resulting in less effectiveness. These differences must be taken into account in making *Bracon* releases.

Parasitization of 15-20% of *Helicoverpa armigera* larvae by naturally *Bracon* will require in a release of 800 parasitoids/ha. The rate is higher (1,000 parasitoids) at 8-12% of parasitized larvae. When cotton borders tomatoes or vineyards, do not release less than 1,500 parasitoids. Rates must vary depending on the phenological state of the crop, e.g., in bloom stage, *Bracon* is retained in the field by the host and by carbohydrate feeding.

Commercial preparations of *Bacillus thuringiensis* (the third biocontrol component) effectively supplements entomophages. The use of dendrobacillin and bitoxibacillin can eliminate 82% of *Helicoverpa armigera*. Subsequently, the quantity of eggs laid (the majority of which are sterile) by the 22-37.9% of deformed adults surviving after treatments of pupated larvae is reduced 2-5 times. Experiments show that it is impossible to protect the crop using one method or technique. Therefore, multiple components may prevent yield losses in any situation in every ecological zone. It is important to carry out control procedures during vegetative periods during overwintering, spring emergence of pests, and autumn formation of overwintering pest reserves.

The complex of introduced cultural practices (soil preparation, weed elimination, and treatment of mulberry trees surrounding cotton fields) results in 27-69% reduction of the overwintering pests. *Trichogramma* are released twice in April and May when noctuid pests emerge and lay eggs onto weeds, young plants of corn, sorghum, tomatoes and alfalfa. Up to four *Trichogramma* releases are recommended against the first generation of *Helicoverpa armigera* in all zones. High temperatures (32°C) during development of the second generation prevent *Trichogramma* from manifesting itself properly. Thus, one treatment with one of the insecticides (sevin, fosolon, thiodan) is carried out in southern regions of Tajikistan (the zone of the most active pest development), while in northern and central regions, *Bracon* are released. The development of the third generation is controlled by dendrobacillin in the south and by 3 *Trichogramma* releases in other zones of the republic. Bacterial preparations are not applied in the zones where *Bracon* is released.

During August or September (at the beginning of cotton harvesting), it is necessary to start the control of autumn formation of overwintering pest reserves. At this time, adults continue oviposition while *Helicoverpa armigera* larvae of the last generation feed and pupate on the late sown and resown fields in plots either with prolonged vegetation period (due to excess of nitrogen fertilizers or close subsoil waters) or neighboring attractive crops (corn, vegetables). In autumn of 1980-1986 in Guissar Valley, *Trichogramma* releases resulted in 28-47% reduction of pest eggs, *Bracon* releases resulted in 32-78% decrease of pest larvae, and dendrobacillin killed 48-76.8% of pests. *Bracon* released in the summer maintained activity in the autumn producing mortality of pest larvae.

Fields receiving few chemical treatments attract more natural parasitoids and predators which create natural barriers while suppressing the reproduction of aphids, spider mites and bugs. Entomophages are not allowed to be used after Bi-58, antio, and fosolon (preparations applied to control aphids and thrips), thus inhibiting pest resistance development. Continuous use of organophosphate insecticides for 30 years has resulted in resistance of aphids, thrips and phytophagous bugs with poor control of *Helicoverpa armigera* and *Tetranychus urticae* as well.

In 1985 (under conditions of the melon aphid outbreak), we managed to follow dynamic changes in resistance level depending on the number of treatments with the organophosphorus preparation, Bi-58. We established that with every subsequent application of the chemical, loss of aphid susceptibility occurred. In the Guissar region resistance increased 16 (LD50 - 0.003 g), 34.5 (0.0069 g), 48 (0.0096 g), and 56 (0.011 g) after 1, 2, 3 and 4 treatments, respectively. In the Tursunzadev region it increased from 94 (0.0039 g) to 94 (0.0186 g) resulting in a decrease in pest mortality decrease from 72.8% to 23.6% in Guissar region and from 71.4% to 14.8% in Tursunzadev region. At the same time, pest numbers increased 4.3-11.5 times and 6.1-17.6 times, respectively. A similar situation occurs in the cotton aphid. Resistance levels were as follows after unreplaced continuous use of Bi-58 and fosolon: from 83 (0.0083) to 92.3 (0.0018) in Guissar region; in Tursunzadev region it constituted 180 (0.018) and 245 (0.0049). Treatments with Bi-58 modelled the situation when the insecticide lost its decreasing yield. Under these conditions, farms were forced to use sumicidin, which reduces aphid numbers by 93.2-98.4% in 5 days after one treatment.

Excess use of Bi-58 against cotton aphid promotes resistance development in the spider mite. Phytophagous bugs began to develop intensively (in July and August - 450-600 bugs/100 plants). Replacement of Bi-58 with sumicidin resulted in the outbreak of the spider mite. In 5, 10, and 15 days after treatment (0.5 kg/ha) pest density increased 2.5-3.8 times, 6.3-11.2 times, and 8.1-14.1 times respectively. This phenomenon cannot be explained by the elimination of entomoacariphages alone. Our experiments show that sumicidin stimulates development of the spider mite creating conditions for formation of 2.5-3 generations more than application of organophosphorus materials. The negative role of chemicals is manifested most of all when choice of pesticides is limited. The following scheme was found to be efficient against aphids:

- weed elimination around fields before cotton sprouting,
- one treatment of marginal stripe of the field with either fosolon or Bi-58 at 10-15% of infested plants, and
- treatment of appearing foci with sumicidin in 20-25% of damaged plants.

Fields with weakened chemical pressure are more eagerly colonized with entomophages (780-920 entomophages/100 plants in the experiments made), which create natural barriers suppressing aphid development. It resulted in an 81-86% increase of Bi-58 effectiveness and 79.7-83.7% rise of that of fosolon. Pest resistance decreased to 8.2(0.00164)-22(0.0044) level.

Application of selective acaricides can control spider mite development and neutralize negative aftereffects of sumicidin. The data obtained show that limited pesticide choice results in the reduction of effectiveness of materials used, and pest outbreaks become inevitable and are then treated again, thereby strengthening negative aftereffects. Rotation of different classes of chemicals increases their effectiveness, and the intervals between treatments may become longer. Foci application of pesticides provides a cleaner environment, more attraction to parasitoids and predators, and formation of the dynamic balance needed for noxious and beneficial species. The number of the latter increases so that it becomes capable of establishing long term control of pest development. Pesticide replacement by *Trichogramma*, *Bracon* and microbiopreparations will increase natural control, and this is the ecological essence of tactics tested in Tajikistan for overcoming negative results of chemicals use and their integration with biocontrol means. Hence, widening of pesticide assortment

is considered necessary and is the key to optimization of chemical pressure in the cotton field. The scheme appended (Kovalenkov 1990) illustrates aftereffects of two approaches: limited and excess use of pesticides.

The area treated is important in stabilizing the effect of biocontrol. In an area more than 100 ha where entomophages are released and interact with natural ones, they exercise more rapid control of the pest, thereby affecting both current and subsequent generations. Mortality of *Helicoverpa armigera* progresses, and pest numbers become economically unimportant. If biocontrol agents are used only in 1-2 fields, there are considerable fluctuations in parasitism parameters because of migration of pests from other fields. In data obtained from the center of a field with the area of 280-690 ha, the effectiveness of entomophages, *Trichogramma* and *Bracon*, was 11-20% and 15-26% respectively -- higher than in the field borders. Hence, the bigger the area under protection colonized with entomophages, the higher and more stable parasitism parameters are, and the more guaranteed the formation of the agrocoenosis is with a balanced ratio of noxious and beneficial pests.

The difference between upper and lower effectiveness thresholds is minimal if *Trichogramma* and *Bracon* disperse simultaneously on several bordering crops thereby improving activity of entomophages. Two to three year integration of biological and chemical methods is necessary for transition from chemical to biological control. This has been observed on cotton, corn and tomatoes.

Chances of higher yield are greater if IPM is carried out on all crops of cotton rotation including corn, alfalfa, vegetables. These other crops are reservoirs for polyphagous pests which accumulate and (under excess density or at the end of vegetation period) migrate to cotton creating additional damage. For example, corn sown for grain and attracting *Helicoverpa armigera* is recommended to be treated with dendrobacillin at the silk stage during mass egg laying and larva emergence. When corn is grown for silage, it should be harvested before pupation of larvae. Late protection measures result in reduced pest development.

On tomatoes, *Helicoverpa armigera* has one more generation and 5-10 times more numerous than on cotton. When 250-300 larvae are present/100 plants, expect migration of subsequent adults to cotton. Thus, it is very important to

control this pest in tomatoes. This problem is successfully solved by release of *Trichogramma* and *Bracon*. Such tactics prevent damage to cotton and produce 13-16 centners of corn grain/ha and 30-100 centners of tomatoes/ha higher yield than chemical treatments.

Pest control effectiveness is affected by time of application of chemical or biological means. Up-to-date control tactics require adequate sampling techniques and determination of optimal time for application. To meet these requirements studies were made of sex pheromones of noctuid pests, and technologies for their application were developed. Prediction of time of chemical application with pheromones reduced chemical treatment numbers by 0.5-1. In 1988, the use of pheromone traps in the area of 97,000 ha reduced chemical costs 1-6 million roubles.

Variation of application time for natural enemies, and their proper selection and rational combination constitute up-to-date scientifically-based integration of knowledge. If chemical treatments are used, they must be carried out to decrease maximum pest numbers as well as preserve entomophages. Different procedures and combinations add to our knowledge of cotton production. Reliable sampling data by hand and with pheromone traps helps decision making on which chemicals to use and the sequence of their use. This tactic determines the degree of biocontrol effectiveness, making IPM flexible, multivariate and capable of increasing yield under any situation in every ecological zone.

Proper selection and rational combinations for protection of crops in cotton have been widely adopted in state and collective farms. In recent years it has become possible to prevent 10-15 centners of cotton losses/ha in the republic and to reduce chemical treatments to 0.5-0.7. Annually the use of insectoacaricides is abolished in the area of 120-180 thousand hectares. The area for release of laboratory reared entomophages increased from 5,000 ha in 1980 to 114,000 ha in 1989. The environment has considerably improved, and, in the process, has allowed the development of apiculture.

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Table 1. The scheme of positive and negative aftereffects of limited and excess application of pesticides.

Limited application	Excess application
Preferential use of biocontrol agents, local treatments with selective chemicals.	Excess chemical pressure.
Stimulation of the activity of natural and colonized entomoacariphages.	Elimination of natural entomoacariphages.
Reduction of pest contacts with pesticides. Increase of their susceptibility to toxicants.	Formation of resistant pest populations.
Controlled development of pests in the range of permissible damage thresholds.	Management pest outbreaks.
Guaranteed yield.	Yield losses.

Genetic Control of Cotton Insects, the Pink Bollworm as a Working Program

R. T. Staten¹

Introduction

The use of genetic control mechanisms for cotton insects has been explored to varying degrees with several insects including the tobacco budworm, *Heliothis virescens* (F.), and the boll weevil, *Anthonomus grandis* Boheman. Its use and actual application on a large scale has been limited, however, to the pink bollworm, *Pectinophora gossypiella* (Saunders). This report will cover that usage and its potential for expansion.

It is important to have a historical perspective of the Pink Bollworm problem in the U.S. At the present time it is a western United States problem restricted to the irrigated desert areas. Pink bollworms are occasionally recovered from the south, east of Texas with only one endemic population on wild cotton in the southern extreme of Florida. The Floridian population has total geographical isolation from any commercial cotton growing area in the U.S.

The pink bollworm is most destructive in Arizona, southern California, and the northwestern Mexican desert cotton growing areas. (Figure 1). Its introduction and establishment in central Arizona in the mid 1950s and into the Colorado River Basin of western Arizona, southern California, and northwestern Mexico in 1965, has led to the development of a major pest problem with extreme side effects on the whole ecosystem. This is, of course, exacerbated by a long growing season which when pushed for maximum production results in tremendous population potential. The extensive use of broad spectrum conventional pesticides including the newer synthetic pyrethroid compounds has resulted in expensive control systems with secondary pest problems. The only major area in the western cotton belt where the impact of the pink bollworm has not been felt by the grower is in the central California San Joaquin Valley. In this area the establishment of pink bollworm has been prevented through the use of sterile insect technology and adequate cultural control. This paper will briefly outline the details and provide program statistics for that project. In addition, it will discuss efforts to integrate sterile release technology with pheromone systems and optimum cultural practices in the heavily infested Southern California desert.

The San Joaquin Exclusion Program

The San Joaquin Valley has never had a known continuous endemic population of the pink bollworm even after the expansion of pink bollworm into the Colorado River desert growing areas in 1965 and 1966. The San Joaquin Valley is separated by approximately 175 miles (direct line) from any generally infested areas of southern California. The entire 175 miles is a host free zone. This expanse of desert and mountains has formed a *partial* barrier to pink bollworm movement. Movement within the desert region between the generally infested southern California deserts and the San Joaquin Valley has been documented by Stern et al. (1978) and by trap lines maintained by program personnel in the mountain passes between the desert cotton growing areas and the San Joaquin Valley. Extensive movement into the desert area has been documented early in the spring, late in the summer, and throughout the fall. Movement over mountain passes into the adjacent San Joaquin Valley has been documented in the fall. Program trap data further supports evidence of movement within the San Joaquin Valley since late season increases in detection have coincided with captures in the desert trap lines. All of this data has been gathered by using gossyplure baited traps placed along highways in the deserts between cotton growing areas.

Sterile insects are now reared in Phoenix, Arizona using techniques or modifications of techniques described by Stewart (1984). Attention to detail and constant refinements of these rearing processes since 1971 has constantly improved the quantity and quality of insects available for shipment.

The increase in quality is illustrated in Table 1, which summarizes quality control mating tests by program personnel. Twenty pairs of sterile males and females are held in cages. Samples are taken each day of shipment (7 days a week) throughout season. Those females which contain spermatophores are considered mated. Table 1 shows an increased mating propensity between 1985 and 1989 after small procedural improvements were made in shipping.

Similar laboratory tests were used to check mortality over a 14 day period. Mortality of 8-10% was normal in 1985 and 1986. However, season-long moth longevity was improved enough to reduce season-long mortality to 5 to 6% in 1989.

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Production capability of the Phoenix facility is illustrated in Table 2. Laboratory space was increased by approximately 15% during the 1970 - 1989 period. All other production increases were technical.

The Phoenix USDA/California Cotton Growers funded facility was the only provider of sterile insects for the San Joaquin Valley from 1970 through 1975 and 1983 through 1990. It has also provided significant numbers of pink bollworm for research work including sterile insect research. These trials included those in the Moapa Valley of Nevada (Staten, unpublished), St. Croix (Henneberry, et al. 1985), and in the Coachella Valley of California. Pheromone isolation and identification projects (Hummel, 1973 et al., Bierl et al. 1974) have also been supported.

From 1976 through 1982 a commercial "satellite" PBW rearing facility was operated for 8 months of each year. This facility provided moths for the San Joaquin Valley.

Sterile insects are shipped at 40 ± 5 degrees fahrenheit from Phoenix, Arizona to Bakersfield, California where they are transferred (still in a chilled condition) to aircraft and released at approximately 500 feet above the cotton fields. The time of collection from eclosion chambers to the time of release is from 24 to 48 hours. Insects are held in an immobile state by chilling during this time.

The sterile and native populations are currently monitored with pheromone traps baited with gossypure in a controlled release formulation. The Delta Trap (Foster et al. 1977) has been used since 1974.

With the advent of gossypure and its availability in 1974 the conduct of this program has become much more precise. For that reason this document will discuss program operations after that time. A summary of pertinent information is shown in Table 3.

Numbers of traps have varied from 12,850 to 33,711. Traps have been placed at average densities varying between one trap per 39.5 acres to one trap per 79.8 acres. Traps are serviced weekly. The data produced by these traps is used to schedule the release of sterile insects. From 1974 to 1989, the area requiring release of sterile insects has ranged from 4.6 percent to 29.5 percent of the total San Joaquin cotton production area.

Each year the season starts with releases on cotton in sections which had moth finds from the previous year. Thus, the percent of the total acres released has varied. As is appropriate (dependent upon native moth capture rates the previous year), buffer zones are also released around these sections. Moth releases are controlled at the section level (640 acres). As new unmarked (native) pink bollworm are found, the releases are adjusted accordingly.

Moth release typically begins before the first flower buds are present on cotton plants (pin square) and continue with daily shipments of moths throughout the season. Releases of sterile insects have been terminated typically each year during the last two weeks of October or the first two weeks of November.

A general overview of the most pertinent trap capture and sterile release data is shown in Table 4. Major improvements in rearing technology and management systems in 1975 represented a significant improvement in program operations. A very dramatic degree of improvement in rearing is seen when one compares the numbers of moths shipped to the San Joaquin in 1975 compared to 1974 (Table 4).

Shipments increased from 37.01×10^6 moths in 1974 to 150.11×10^6 in 1975, and 1976 at 173.6×10^6 in 1976. Although native unmarked populations were low early in 1974, it became apparent that a major problem existed as the season progressed. The total sterile moth captures of 282,897 was 647 times higher than the non sterile recovery, but acceptable working ratios at the individual field level could not be maintained when native populations became very heavy in August and September. (Note: Through experience, the ratio of 60 sterile moths to one native moth has been established as a working, safe ratio.) It was very fortunate that improvements were brought on line before the 1975 season. The production in 1975 was able to cover the entire infested area adequately.

Relatively high native moth capture (1,474) late in the season in 1976 followed tropical storms off Baja California, Mexico and resulted in a decision to augment sterile moth production at the USDA facility in 1977 by outside contract production. This contract provided 28 percent of the 412 million moths used in the San Joaquin in 1977 and provided an average of 39 percent of all production until the 1983 season. In 1983, the 586 million moths shipped were provided exclusively by the USDA facility in Phoenix.

In 1980 we captured the biggest number of native moths in program history. Unlike 1974, however, coverage of the entire area where moths were detected was achievable throughout the season. Major efforts were also made through grower meetings throughout this area to optimize better cultural controls.

The following year 24% of the Valley received sterile insects. This rate is high in comparison to the preceding few years of release, but with good winter mortality between the 1980 and 1981 season it was apparently adequate. We have not had buildups of these levels again.

When one tries to assess this program with its massive number of traps and extensive amounts of data they generate, it is apparent any analysis would be highly speculative in nature. There are no check plots and/or adjacent identical infested areas.

It should also be noted that until the present time we have used resources on an as available basis. We are now constructing in APHIS, with cooperation from Texas A&M University a heuristics-based expert system to help the decision maker utilize the extensive data base that this project generates. So, although the project has its limitations, two pertinent points have not been missed by the cotton industry. The first is that there is not a detectable ongoing pink bollworm population in the San Joaquin Valley, and second that our rearing technology has improved significantly and consistently over the years.

The Integration of Sterile Insect System With Pheromone Disruption

Once the pink bollworm spread into the Colorado River Basin (Figure 1), the entire cotton pest management system changed drastically. Cotton growers were determined to continue maximizing yields and were quick to utilize regularly scheduled insecticide application. This philosophy continued essentially unabated for approximately 20 years. In the most severely infested areas (such as the Imperial Valley) grower leadership is now seeking other remedies. In addition to working with sterile insect technology, our laboratory, the Agricultural Research Service, and industrial cooperators have worked extensively for the development of pheromone communication disruption. The large scale field testing of the Mitsubishi PBW rope in 1985 (Staten et al. 1987) in the Imperial Valley

provided a breakthrough. This breakthrough led to the conduct of an "area wide" management project in the Coachella Valley on its restricted acreage.

The Coachella Valley is reasonably isolated during the main growing season and measurably affected by migration only during storm conditions that include surface winds from the southeast, usually late in the season.

In 1986 we started working in a cooperative venture with the growers of the area and their pest control advisor (M. Grummet of Foster Gardner Chemical Co.). Our first step in 1986 was to treat the entire valley with the high rate PBW rope system, at 30 grams active ingredient (AI) per acre, in one application, at the 6-8 leaf cotton development stage. Our results were encouraging enough that in 1987-1989 we started releases of sterile insects at 500+ sterile pink bollworms per day. This was done in connection with a minimum shortening of the growing season. Under this system, sterile insect release started at the 3-4 leaf cotton stage. The pheromone was only applied at the 6-8 leaf cotton stage. If a ratio of 60:1 sterile to native insects was not achieved in a given field at a 6 leaf stage, that field received a pheromone treatment. Thus, while not all fields would receive pheromone, all fields received sterile insects. At any time in the season that chemical control thresholds were exceeded, the grower and his pest control advisor were expected to utilize chemical control to complete the growing season. This treatment was on a field by field basis as needed.

Pink bollworm sterile and native populations were monitored with Delta traps at 2 traps per 40 acres and with boll samples collected in each field (80 to 100 bolls per field each week). Bolls were then returned to the laboratory for examination under large lighted 3x magnification lenses. Samples were taken from the second week in July through August.

Management Trial Results: The overall treatment strategies, pheromone usage, and insecticide use patterns are shown in accompanying Table 5.

Before 1986 the preponderance of the cotton growers in the valley used expensive multiple chemical pesticide applications for control of PBW even though in this valley other crops such as grapes, dates, citrus, and vegetables were considered more important and placed on the better land. Cotton is usually grown on more marginal ground at as

low a cost as possible. In the most successful year, 1988, no conventional organic insecticides were used. In this year, pink bollworm movement from the Imperial Valley to the Coachella Valley was not significant until the last weeks of August as detected by traps in the desert between the two valleys. In 1989 the Imperial Valley terminated its cotton by cessation of all irrigation in early to mid August. All fields were defoliated chemically by September 1, with 12 exceptions out of over 130 fields. Movement was very apparent across the desert from the last weeks of July and throughout August. Our control with minimal insecticide in the Coachella Valley was still acceptable as illustrated by both pesticide use patterns and by low larval populations as shown in Table 6, which summarizes larval population levels through August in all four years.

It should be noted that, although usage of conventional insecticides was being restricted significantly, the overall population levels were held at drastically reduced levels. This is particularly true in comparison to the larval populations in the Imperial and Parker Valleys in 1989. This may be noted in comparing our data with that from cooperative monitoring projects in Imperial (D. Weddle, C. C. Chu, R. T. Staten, T. J. Henneberry, and S. Birdsall, unpublished) and a Parker, Arizona project (R. T. Staten, L. Antilla, F. Myers, and R. Crout, unpublished) Table 7.

The population of larvae in Table 5 are from boll samples taken season long in 45 fields in Parker, Arizona, and 55 fields in the Imperial Valley, California. All fields were under conventional insecticide treatment.

Summary - Future Prospects

The twenty three year history of the San Joaquin Valley exclusion project is considered by the California cotton industry as a major success. The industry funds their program at better than 85% of its total cost, and has opted to spend 2.1 million dollars for two new rearing buildings with options for major expansion to continue this program.

In addition, these same growers are in pursuit of an expanded trial in the Imperial Valley. The Imperial Valley is ideal as a target to expand these techniques because it has a much larger acreage than Coachella and is, as a cotton growing area, under extreme duress. Normal cotton production of 40-80,000 acres has been the rule in the past years. Cotton production has slipped to approximately

10,000 acres largely due to the extreme cost of treating pink bollworm infestations. In addition, the growers in that community have opted to drastically shorten the growing season with marked impact on pink bollworm population. Our laboratory, in cooperation with the Imperial County Commissioner of Agriculture, and Agricultural Research Service, monitored the pink bollworm population extensively in 1989 before any winter cultural program could affect the population of that year. Populations were thus mentioned in an identical fashion in the season of 1990, following a mandatory fall termination in 1989. Populations have been drastically reduced as evidenced by adult moth counts in delta traps and boll infestation data. In addition major test releases this year clearly indicate a 500 sterile moth per acre per day release is feasible. I expect that by next year an even lower release rate would be effective at achieving a 60:1 ratio. My reason for this optimism is found in a comparison of boll sample data collected from boll incubation boxes. In 1989 versus this year, 1990, drastically lower populations have already been noted. Our data is far from complete. Table 8 contains a summary of July's data.

This data was taken largely from a non-sterile release zone. As these population trends advance, I expect an even lower overwintering survival for the 1991 season. Sterile releases will become more economically feasible.

The importance of these approaches and the necessity of finding a better management scenario are imperative in today's ecologically concerned society. We can no longer live with major insecticide usage for pink bollworm and its associated secondary pest problems. In addition, we can not keep ahead of insecticide resistance for key pests such as the pink bollworm and the white fly species now found in cotton. We must reduce environmental hazards from pesticide use, including drift and residue. The pink bollworm problem with today's knowledge can only be dealt with in an organized area wide rational basis.

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Table 1. Annual Summary of Mating propensity of sterile Pink Bollworm females shipped to the San Joaquin as determined in the laboratory for 1985 through 1989

Year	% Mated
1985	43
1986	70
1987	81
1988	76
1989	86

Table 2. Annual Production of the Phoenix Pink Bollworm Rearing Facility, 1970 through 1989

Year	Total Moths x 10 ⁶
1970	135
1971	120
1972	113
1973	99
1974	41
1975	154
1976	177
1977	192
1978	301
1979	385
1980	372
1981	401
1982	497
1983	594
1984	579
1985	489
1986	702
1987	735
1988	804
1989	826

Table 3. General Statistics for the San Joaquin program for 1974 through 1987

Year	no. acres mapped x10 ³	no. traps maintained x10 ³	acres per trap x 10 ³	maximum acres released x10 ³	percent acres released	mean no. steriles per acre
1974	1,275	32.0	39.5	101	7.9	366
1975	866	22.0	40.0	117	13.1	1,287
1976	1,130	27.0	41.0	90	7.9	2,141
1977	1,353	33.7	40.0	400	29.5	1,030
1978	1,501	19.6	76.3	355	26.6	1,286
1979	1,625	20.6	78.8	254	15.6	2,512
1980	1,463	20.8	70.2	177	12.1	2,880
1981	1,451	19.4	74.8	352	24.3	2,251
1982	1,326	16.9	78.3	147	11.0	5,260
1983	1,005	12.9	78.2	132	13.1	4,452
1984	1,392	17.6	79.0	42	6.1	13,329
1985	1,336	17.2	77.9	59	4.6	8,167
1986	1,061	13.3	79.8	44	4.1	14,930
1987	1,368	22.7	60.4	71	5.2	10,655
1989	1,128	19.2	58.8	104	9.2	7,258

Table 4. Sterile Moth Release and Total Moth Capture Data in the San Joaquin Valley

Year	Sterile Moths Released x10 ⁶	Percent Sterile Recovered	(Native) Sterile Moths Recovered	Non-Sterile Recovery (Native)	Sterile Insects Captured per Native
1974	37.01	0.76	282,897	437	647.0
1975	150.11	1.01	1,528,260	245	623.8
1976	173.64	0.63	1,229,742	1,474	834.0
1977	412.17	0.40	1,677,900	7,402 ¹	22.0
1978	455.99	0.09	429,063	69	621.8
1979	636.98	0.09	545,295	754	723.0
1980	510.49	0.11	566,170	4,492 ¹	126.0
1981	794.26	0.11	864,861	677	127.7
1982	772.12	0.13	1,041,280	120	8,677.3
1983	586.77	0.18	1,057,735	863 ¹	1,225.6
1984	571.50	0.38	2,144,018	351	6,108.3
1985	483.74	0.09	434,739	160	2,717.1
1986	660.35	0.05	352,825	62	5,690.7
1987	670.07	0.15	1,057,925	294	3,598.7
1988	754.87	0.16	1,188,335	891	1,335.7

¹ Finds of 4, 9, and 4 larvae in respective years

Table 5. Control strategies and conventional insecticide use patterns for pre-management and area-wide management systems in the Coachella Valley.

Treatment System		Fields Treated with Pheromone	x No. Conv. Insecticides	No. Fields Treated with Insecticides	Cumulative Conv. Insect. Treatments
1985	Insecticide only (Pre-trial data)		7.27	56/57	414
1986	Pheromone and Insecticide	31/31	1.80	17/31	56
1987	Sterile Insects, Pheromone and Insecticides	17/27	1.03	7/27	28
1988	Sterile Insects and Pheromone	4/31	0.00 ¹	0/31	0
1989	Sterile Insects, Pheromone and Insecticides	3/23	1.90	18/23	44

¹Most importantly, we have achieved major reductions in conventional pesticide usage in the four years that we have operated this program with combined pheromone and sterile insect strategies as shown in table 5.

Table 6. Summary Boll Data - Coachella Valley Pink Bollworm Management Study Showing Total Larvae per Sample and Number of Bolls Sampled

Week	1986		1987		1988		1989	
	No. Bolls Sampled	Total Larvae	No. Bolls Sampled	Total Larvae	No. Bolls Sampled	Total Larvae	No. Bolls Sampled	Total Larvae
1	50	3			370	0		
2	500	3	500	0	726	0	560	0
3	960	2	1,700	0	1,200	0	720	0
4	1,180	9	2,400	7	1,600	1	960	0
5	1,520	1	2,400	33	2,000	0	1,520	0
6	1,520	3	2,500	34	2,160	0	1,600	1
7	1,600	0	2,700	11	2,320	0	1,760	0
8	1,520	1	2,700	6	2,480	0	1,564	18
9	1,600	1	2,700	5	2,480	5	1,860	39
10	1,760	43	1,350	25	2,480	1	1,960	39
11	2,200	138	1,350	41	2,480	0	1,240	47

Table 7. Data from Boll Surveys Selected Randomly from Fields in Imperial Valley, California, and Parker, Arizona, and all Coachella Fields in 1989

Date	Number of Larvae per 100 Bolls		
	Imperial Valley ¹	Coachella	Parker
7/01 - 7/05	----	0.00	----
7/06 - 7/14	7.84	0.00	----
7/17 - 7/21	8.84	0.00	----
7/24 - 7/28	9.50	0.06	3.16
7/31 - 8/04	11.40	0.00	5.40
8/07 - 8/11	15.34	1.15	11.05
8/14 - 8/18	25.10	1.99	16.20
8/21 - 8/25	30.70	1.98	18.86
8/28 - 9/01	34.34	3.80	21.89
9/03 - 9/06	----	----	23.02
9/10 - 9/13	----	----	16.98
9/24 - 9/27	----	----	14.15

¹ Data adjusted from Boll Box Survey to equate with standard cutting procedures (Henneberry et al. 1985).

Table 8. Comparative Larval Infestation in the Imperial Valley before and after reduction in season length, expressed as larva per 100 bolls.

	1989	1990
July 6 - July 14	15.6	0.67
July 17 - July 21	17.6	0.37
July 24 - July 28	19.0	2.46
July 30 - August 4	22.8	3.20

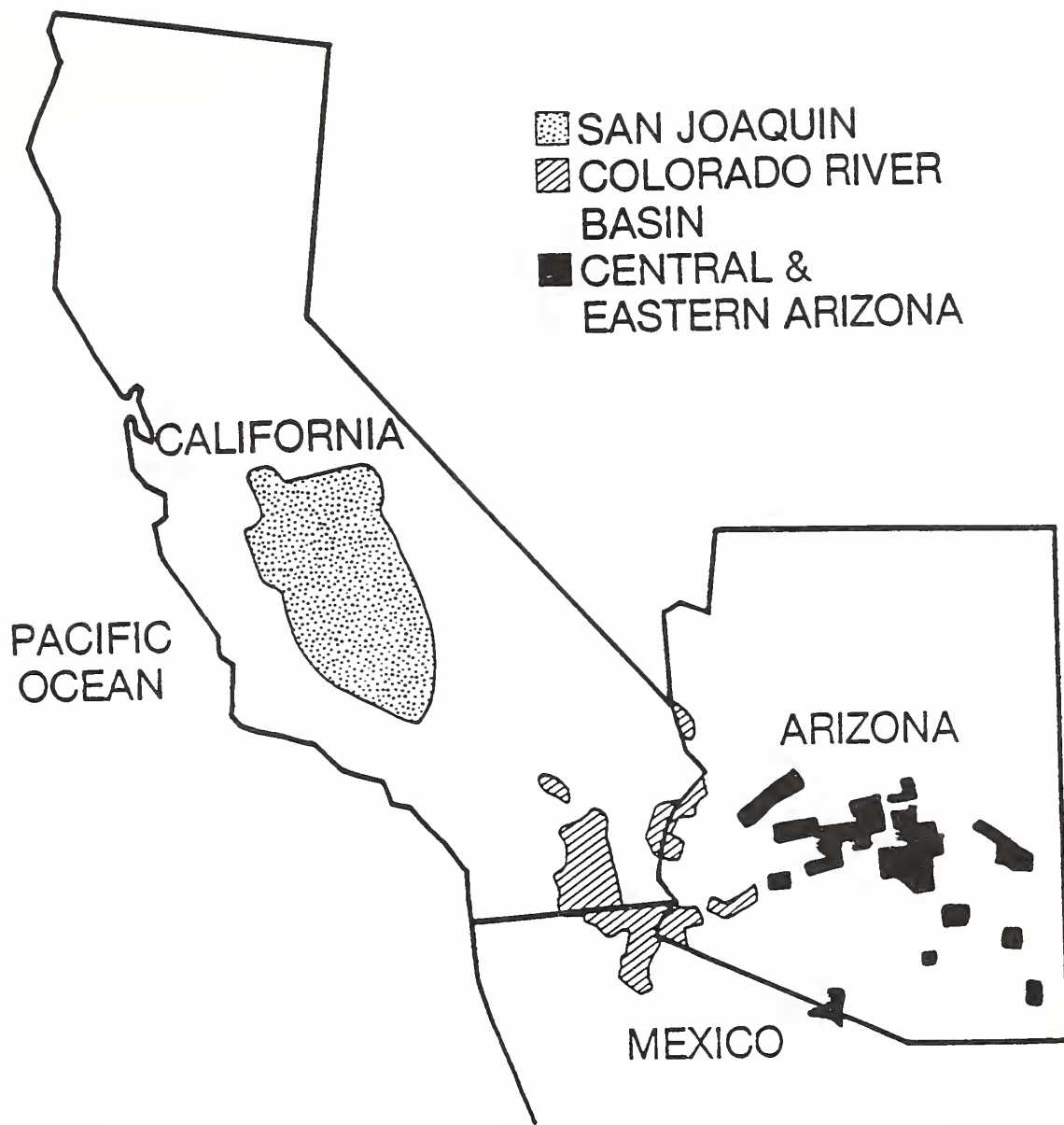


Fig. 1. Cotton growing areas of the western United States (Arizona and California) and northwestern Mexico

Cultural Control of Cotton Insect Pests, with Emphasis on an Emerging Program of Cultural Controls in the Lower Rio Grande Valley of Texas

Kenneth R. Summy and Edgar G. King¹

Abstract

During the past two decades, cotton production in the United States has largely shifted from production systems heavily dependent on broad-spectrum pesticides to systems utilizing an array of cultural and biological controls. Cultural controls embody an array of potential pest-control tactics, ranging from initial cultivar selection to a sequence of agronomic practices which commence prior to planting and terminate following harvest. Many of these strategies are singularly effective against one or more cotton insect pests, and may become particularly potent when used in conjunction with other cultural practices in an organized community-wide pest management effort. The principal cultural practices employed against cotton insect pests in the United States are discussed, and an emerging program of cultural controls in the Lower Rio Grande Valley of Texas (U.S.A.) is summarized.

Introduction

Cotton production in the United States has traditionally been plagued by serious losses to insect pests, the most important of which are the boll weevil, *Anthonomus grandis* Boheman, pink bollworm, *Pectinophora gossypiella* (Saunders), bollworm, *Helicoverpa* (= *Heliothis*) *zea* (Boddie), tobacco budworm, *Heliothis virescens* (Fabricius), sweetpotato whitefly, *Bemisia tabaci* (Gennadius) and a complex of plant bugs which includes the cotton fleahopper, *Pseudatomoscelis seriatus* (Reuter), tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois), and *L. hesperus* Knight. During 1974-1976, an estimated 201.6 million bales were destroyed by boll weevil alone, which represented a total annual loss of ca. \$145.5 million (DeBord 1977, Schwartz 1983). During 1989, arthropods accounted for a loss of ca. 1.1 million bales and a total expenditure of ca. \$686 million (Herzog and King 1990).

Newsom and Brazzel (1968) partitioned the history of cotton pest control in the United States into two distinct periods: 1) prior to the invasion of boll weevil (ca. 1892), in which losses to insect pests were generally moderate and

emphasis was placed on cultural and biological controls, and 2) thereafter, in which losses to insect pests became substantial and chemical control became predominant. The chemical control era was further separated into four distinct periods characterized by 1) a continuing emphasis on cultural and biological controls (1908-1923), 2) extensive use of calcium arsenate (1924-1945), 3) dependency on chlorinated hydrocarbon insecticides (1946-1955), and 4) unilateral reliance on organophosphate insecticides (1956-1968). The latter period culminated with the development of organophosphate-resistant populations of tobacco budworm, which precipitated a series of crop disasters and shattered the illusion that cotton could be produced indefinitely in this manner (Adkisson 1971).

The concept of "integrated control" was originally defined as the use of insecticides in a manner least detrimental to biological control agents (Bartlett 1956). More recently, this definition was broadened to the effect that "all necessary techniques are consolidated into a unified program, so that populations can be managed in such a manner that economic damage is avoided and adverse side effects are minimized" (National Academy of Sciences 1969). These necessary techniques include a broad range of cultural controls, defined as the "purposeful manipulation of the environment to make it less favorable, thereby exerting economic control of the pests or at least reducing their rates of increase and damage" (National Academy of Sciences 1969).

Considerable emphasis has been placed on cultural control of cotton insect pests during the past two decades (see reviews in Noble 1969, Walker 1984, Bradley et al. 1986, Luttrell et al. 1986, Rummel et al. 1986, Henneberry 1986, Walker and Smith, in press). Cultural strategies encompass a potential arsenal of tactics, ranging from the initial cultivar selection to a sequence of agronomic practices commencing prior to planting and terminating after harvest. These methods, in conjunction with the fundamentals of insect pest and beneficial insect sampling and economic thresholds, provide a strong base for ecologically-oriented pest management systems.

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Components of Cultural Control

Cultivar Selection

Cotton breeders have expended considerable effort in attempts to develop cultivars resistant to arthropod pests and pathogens (see reviews by Jenkins 1982a, 1982b, Jenkins et al. 1969, Maxwell et al. 1972, Schuster and Frazier 1976, Jones et al. 1978, Lukefahr 1977, Schuster 1979, Niles 1980, Adkisson and Dyck 1980, Adkisson et al. 1982, Wilson 1982, Namken et al. 1983, Walker 1984, Bridge and McDonald 1987, El-Zik and Thaxton 1989, Jenkins and Wilson, in press). These efforts have traditionally concentrated on two principal approaches: varietal resistance and earliness.

Varietal Resistance

Painter (1951) defined the components of host plant resistance as 1) antibiosis, i.e., factors which reduce pest survival, prolong developmental time, or produce other effects detrimental to the pest, 2) nonpreference, i.e., factors which tend to reduce the incidence of pest attack relative to a more susceptible counterpart, and 3) tolerance, i.e., factors which allow a cultivar attacked by the pest to produce a yield greater than that of a less tolerant counterpart. A considerable number of resistance factors have been identified and incorporated into experimental and commercial cotton cultivars. Several of the important insect-resistance characters in cotton have involved modification of leaf shape, structure or color. Pilosity (pubescence) confers resistance to boll weevil, pink bollworm and plant bugs (Wannamaker 1957, Wilson and Wilson 1975, Meredith and Schuster 1979), while glabrous (smooth leaf) cottons exhibit variable degrees of resistance to bollworm, pink bollworm and whiteflies (Lukefahr et al. 1971, Schuster 1979, Butler and Wilson 1984, Butler and Henneberry 1984, Butler et al. 1986, Berlinger 1986). The okra-leaf and super okra-leaf traits facilitate penetration of insecticides within plant canopies and appear to increase resistance to pink bollworm and whiteflies (Jones et al. 1975, Berlinger 1986, Wilson 1987). Red pigment confers resistance to bollworm (Bhardwa and Weaver 1983) and appears to hinder detection of plants by boll weevil (Isely 1928); once detected, however, red cottons are as susceptible to boll weevil damage as green cottons (Hunter et al. 1965). Nectariless cotton (devoid of extrafloral nectaries) has been shown to reduce damage by bollworm, pink bollworm, cotton leaf perforator, *Bucculatrix thurberiella*

Busck, and plant bugs (Lukefahr and Rhyne 1960, Lukefahr et al. 1971, Henneberry et al. 1977, Meredith et al. 1973, Schuster et al. 1976, Bailey et al. 1980, Bailey 1982, Bailey et al. 1984). Several resistance characters have involved modifications of the floral structures and levels of secondary plant substances, i.e., allelochemicals. Examples of the former include male sterility (reduction in anthers) which confers resistance to boll weevil (Jones et al. 1978), yellow or orange pollen mutants which exhibit resistance to tobacco budworm (Bailey 1981, Hanney et al. 1979), and frego bract, which appears to be one of the more promising resistance characters for boll weevil (Jenkins et al. 1969). Examples of the latter include high levels of gossypol, which confers resistance to bollworm and plant bugs (Bottger and Patana 1966, Lukefahr and Houghtaling 1969, Schuster and Frazier 1976), and condensed tannins, which confer resistance to bollworm and spider mites (Schuster 1979, Lane and Schuster 1979).

One of the recurrent problems associated with plant breeding has been the fact that resistance factors effective against one pest species may increase susceptibility to another pest or group of pest species. Schuster (1979) summarized some of the well-documented examples of this apparent antagonism: 1) pilosity, which confers resistance to boll weevil, pink bollworm and plant bugs, increases susceptibility to bollworm, 2) the glabrous trait, which confers resistance to pink bollworm and bollworm, increases susceptibility to plant bugs (Meredith and Schuster 1979), and 3) frego bract, which reduces oviposition by boll weevil, increases susceptibility to plant bugs (Scales and Hacskeylo 1974, Jones 1972, Tingey et al. 1975). This dilemma has been addressed by the concept of multi-adversity resistance (MAR), which involves the direct or indirect selection for genes or traits that provide resistance to a broad range of adversities, including insect pests and pathogens (El-Zik and Thaxton 1989). An example of the MAR approach would be the combination of frego bract and the nectariless trait in a single cultivar to provide concurrent resistance to boll weevil and plant bugs (Jones et al. 1983).

A second potential problem associated with breeding pest-resistant cultivars involves the possibility that certain resistance factors might adversely impact populations of beneficial predators and parasites. For example, nectariless cottons have been shown to reduce densities of certain predators which habitually feed on extrafloral nectaries, e.g., *Chrysoperla* spp. (Schneider et al. 1986). Field

studies of natural enemy performance on resistant cultivars have produced variable results: for example, Lingren et al. (1978) concluded that resistant cottons did not adversely impact the bollworm parasite *Campoletis sonorensis* (Cameron), while Mussett et al. (1979) noted a 69 percent reduction in predatory arthropods on resistant cultivars compared to a susceptible standard. While generalities regarding the compatibility of plant resistance characters and biological control agents appear somewhat problematic (see Painter [1951] and Adkisson and Dyck [1980] for conflicting viewpoints), any given effect will most probably depend on the particular trait and natural enemy species involved (see reviews in Boethel and Eikenbary [1986]).

Earliness

The second major approach to cotton breeding has involved selection for rapidly-maturing cultivars which (while technically not considered resistance *per se*) provide the means to escape or evade pest damage. The development of rapidly-maturing cultivars was among the initial recommendations for control of boll weevil (Howard 1896, Bennett 1904, 1908, Mally 1901, Newell and Rosenfield 1909) and received major emphasis prior to the synthetic pesticide era commencing shortly after World War II. Rapidly-maturing cultivars were again reemphasized following the "Heliothis" disasters of the 1970s (Adkisson 1971, Wilson 1974) and currently provide the foundation of the "short-season" production systems that have been widely adopted in many areas of the United States (Adkisson et al. 1982). Bridge and McDonald (1987) noted that rapidly-maturing cultivars developed during the past two decades have reduced the growing season (time from planting to harvest) by 28-33 days and have provided higher average yields. Although entomologists at the turn of the century obviously appreciated the value of earliness for control of pests such as boll weevil, the ecological basis of the "short-season effect" was elucidated much later in two important studies. Walker and Niles (1971) detailed the process of boll weevil reproduction as it interfaces with fruiting patterns of cotton. These authors documented the capability of rapidly-maturing cultivars to set an adequate crop of 12-day-old bolls (which tend to be less susceptible to boll weevil damage than younger counterparts) provided two conditions are met: 1) that fewer than ca. twenty female boll weevils per acre are initially present, and 2) that boll weevil densities remain below damaging levels during a critical 30-day blooming period. Parker et al. (1980) further documented that the second condition could be achieved if weevil densities were maintained at or below ca. 1,500

punctured squares per acre during the overwintered generation, i.e., during the prebloom period. Results of the latter study clearly demonstrated that the use of new rapidly-maturing cultivars, in conjunction with narrow-row planting (<40-in) and preemptive insecticidal applications (1-3 treatments for overwintering boll weevils), could result in acceptable yields (500-750 lbs/acre) in the presence of the pest. In addition to these effects on boll weevil, earliness has long been recognized as a means to reduce damage by pink bollworm (Fenton and Owen 1931, Chapman and Cavitt 1937, Fife et al. 1947). The development and adoption of rapidly-maturing cotton cultivars, in conjunction with other cultural strategies such as the use of defoliant and desiccants, has largely eliminated pink bollworm as a pest of cotton in most regions of Texas (Adkisson et al. 1982). This same approach appears to have considerable potential for reducing pink bollworm damage in the arid production regions of the Far West (Walhood et al. 1983), and currently provides a basis for management of bollworm and tobacco bud-worm populations in much of the south-western United States (Rummel et al. 1986).

Transgenic Cottons

A more recent and novel approach to plant breeding has utilized the techniques of recombinant DNA technology in an attempt to genetically engineer cultivars resistant to insect or disease pests (Schmidt 1990). Using a transformation system based on the soil microbe *Agrobacterium tumefaciens*, researchers have successfully incorporated genes of *Bacillus thuringiensis* which code for the production of the delta-endotoxin (toxic to many lepidopterous pests) and the cowpea trypsin inhibitor (which encodes a serine protease inhibitor) into cotton plants (Fillatti et al. 1989). Such toxin-producing plants produce an effect similar to that of conventional insecticides; however, the relative specificity of the *B.t.* delta-endotoxin is expected to be considerably less disruptive to biological control agents than synthetic insecticides (Gould and Weissinger 1990). The probability that commercial adoption of genetically-engineered cultivars will intensify selection pressure for *B.t.*-resistance has been recognized (McGaughey 1990) and several strategies to ameliorate the problem have been proposed: 1) planting mixtures of resistant and susceptible plants, 2) expression of toxins at levels that slow pest growth and reproductive rates, 3) use of tissue-specific promoters that cause only high levels of toxin-gene expression in damage-sensitive plant parts, and 4) use of inducible promoters that are triggered only when a threshold of

damage is exceeded, or by an inducing agent applied by the producer (Gould and Weissinger 1990).

In addition to the development of pest-resistant cultivars, a major emphasis of genetic engineering involves increasing tolerance to various herbicides (Fillatti et al. 1989, Collins 1990). The role of biotechnology in agriculture, and recent developments in cotton culture, are summarized in a number of recent articles (Baker and Dunn 1990, Jenkins and Parrott 1990, Leemans et al. 1990, Umbeck et al. 1990).

Agronomic Practices

Planting Date

Entomologists concerned with the control of boll weevil at the turn of the century were adamant in their recommendations for planting at the earliest possible date as a means to enhance earliness (Howard 1896, Mally 1902, Bennett 1904). While early planting remains a basic tenet of most "short-season" production schemes (Namken et al. 1983), producers in at least one major production region (the Rolling Plains of Texas) have adopted a somewhat different approach. Based on detailed studies of boll weevil diapause and overwinter survival (Rummel and Adkisson 1970, White and Rummel 1978, Slosser 1978, Rummel and Carrol 1985), a uniform delayed planting strategy was developed in the Texas Rolling Plains as a means to maximize suicidal emergence of postdiapause weevils (Slosser 1978). During the past decade, this program has significantly reduced losses to boll weevil and substantially increased the profitability of cotton production in the region (Walker 1984, Masud et al. 1984). Several workers have suggested that a similar program of uniform delayed planting might effectively suppress damage by pink bollworm in the southwestern United States (Adkisson et al. 1962, Henneberry 1986).

Planting Density and Row Configuration

Recommendations for planting configuration at the turn of the century generally stressed relatively low plant densities and wide row spacing as a means to increase mortality of developing boll weevils by direct exposure to sunlight (Mally 1902, Hunter 1904a, 1909, 1912, Hunter and Pierce 1912) or to enhance the effectiveness of indigenous natural enemies (Pierce et al. 1912). Eventually, the advantages of relatively high plant densities and narrow row spacing were

recognized (as means to enhance earliness) and the conventional 40-in row configuration was widely adopted (Cook 1913, Martin et al. 1923, Reynolds 1926, Ware 1930, Cotton and Brown 1934). Narrow-row (30-in) configurations have been shown to accentuate the effect on earliness (Niles 1970; Heilman and Namken 1987; Heilman et al. 1986, 1989; Kerby et al. 1988) and are becoming increasingly commonplace as the appropriate implements become available from industry.

Fertilization and Irrigation

Efficient cotton production in many areas of the United States is dependent on fertilization and irrigation; however, excessive use of either may create conditions conducive to outbreaks of certain pest species, e.g., members of the bollworm-budworm complex (Fletcher 1941, Adkisson 1958, Wilson et al. 1980). Thus, current recommendations generally stress moderation in the use of both inputs. Recent studies have demonstrated that the timing of irrigation may be used to considerable advantage: for example, Slosser (1980) noted that bollworm damage in the Texas Rolling Plains could be reduced substantially by abstaining from irrigation for ca. 7-10 days prior to peak moth flights, and for 3-4 days thereafter (irrigations were scheduled using the simulation model MOTHZV-2 [Hartstack et al. 1976], one of several simulation models currently available to producers for similar purposes). Moreover, early termination of irrigation has been shown to accelerate crop maturity and appears to be of considerable importance in control of late-season pink bollworm infestations in the southwestern United States (Watson et al. 1978, Henneberry 1986).

Plant Growth Regulators and Harvest-Aid Chemicals

Several of the plant growth regulators and harvest-aid chemicals registered for use on cotton appear to have considerable potential for suppression of late-season pest infestations. Mepiquat chloride (PixR) applied to curtail vegetative growth may compensate, in part, for the adverse effects of high fertilization and irrigation rates, although the impact on pest infestations is not entirely clear (Bradley et al. 1986). Defoliants and desiccants applied to facilitate harvest also effectively remove late-season squares and bolls, which contribute little to harvest but are critically important in the initiation of adult diapause in boll weevil (Brazzel and Newsom 1959) and larval diapause in pink bollworm (Lukefahr 1961, Adkisson et al. 1966). Timely application of harvest-aid chemicals has been shown to effectively suppress late-season infestations of both pest

species (Adkisson 1962, Cleveland and Smith 1964, Rice et al. 1971, Mauney et al. 1972, Kittock et al. 1978, Bariola et al. 1976, 1981, 1987, 1990, Hopkins and Moore 1980, Henneberry and Bariola 1985). Henneberry (1986) noted that chemical crop termination is among the most promising approaches to late-season management of pink bollworm in the Far West.

Stalk Destruction

Early destruction of cotton stalks was among the initial and most adamant recommendations for control of boll weevil (Howard 1986, Mally 1901, 1902, Sanderson 1903, Hunter 1904a, 1904b, 1907, 1909, Newell 1906, Hinds 1908) and pink bollworm (Orlendorf 1926, Gaines 1952, Adkisson and Gaines 1960, Noble 1969). The rationale of stalk destruction in temperate environments is similar to that discussed for harvest-aid chemicals, i.e., to destroy the food resources required for initiation of adult diapause in boll weevil and larval diapause in pink bollworm. In addition to these effects, early stalk destruction in subtropical and subtropical environments provides one of the few means available to curtail or eliminate boll weevil reproduction (Summy et al. 1988a) and overwinter survival in desiccated bolls, a phenomenon which has been documented in temperate environments (Cowan et al. 1963, Walker and Shipp 1963) and is particularly commonplace in the Arizona-California region and much of southern Texas (Fye et al. 1970, Bergman et al. 1982, 1983a, Bariola et al. 1984, Guerra et al. 1984, Summy 1990, Summy et al. 1988a, 1988b, Henneberry et al. 1989).

The few organized stalk destruction programs that have been adequately evaluated have generally indicated a dramatic suppression of overwintering boll weevils (Hunter 1907, 1912, Newell 1909, Isely 1930, Gaines 1952, Gaines and Johnson 1949, Summy et al. 1988b). The importance of early stalk destruction is perhaps best exemplified by the experience with "stub" or "ratoon" cotton in the southwestern United States, which has invariably generated major outbreaks of both species (e.g., Bergman et al. 1983b). Early stalk destruction, in conjunction with other cultural controls, played a key role in the demise of pink bollworm as a cotton pest in most regions of Texas (Reynolds et al. 1975, Adkisson et al. 1982).

Tillage

Plowing and other forms of tillage may cause considerable mortality of insect pests overwintering as diapausing larvae or pupae within the former cotton environment, e.g., pink bollworm (Watson 1980) and members of the bollworm-budworm complex (Barber and Dicke 1937, Fife and Graham 1966, Hopkins et al. 1972, Young and Price 1977, Rummel and Neece 1989). Barber and Dicke (1937) noted that overwintering survival of bollworm was reduced most by fall plowing and least by fall disking, and documented a significantly greater overwintering survival in red clay soils compared to sandy loams. Overwintering survival in tilled soils at two locations (0.3-1.6 percent in Virginia and 7.8-13.5 percent in Georgia) was significantly lower than that occurring in untilled soils at the same locations (9-10 percent and ca. 30 percent, respectively). Roach (1981) documented a significant reduction in bollworm emergence from plots subjected to double-disking (1,746 moths/ha) and subsoiling-bedding (3,007 moths/ha) compared to emergence from undisturbed plots (7,760 moths/ha). More recently, Rummel and Neece (1989) monitored overwintering survival of bollworm during a three-year period in the Texas High Plains and documented a significant reduction in overwinter survival in cultivated plots (0-0.2 percent) compared to noncultivated counterparts (2.0-30.9 percent).

Deep plowing has been shown to significantly reduce overwinter survival of boll weevil and pink bollworm infesting cotton bolls (Watson 1980, Henneberry 1986, Henneberry et al. 1990). The practice has been mandated by law in southern Texas as a means to destroy root systems of cotton stalks which would otherwise produce lush regrowth (which constitutes a nearly-optimal overwintering habitat for pests such as boll weevil) during much or all of the fall and winter period (Summy et al. 1986a, 1988a, 1988b). Moreover, deep plowing may significantly reduce the incidence of certain cotton pathogens, e.g., bacterial blight, *Xanthomonas malvacearum*, and root rot, *Phymatotrichum omnivorum* (Presley and Bird 1968).

Habitat Manipulation

The cultural strategies discussed thus far involve manipulation of various elements within a single crop environment to render conditions less favorable to one or more pest species. An additional group of strategies has been designed to manipulate pest densities to advantage within the crop ecosystem (including native vegetation and

unrelated crop species) and/or to increase the effectiveness of natural enemies (see reviews by Herzog and Funderbunk 1985, Stinner and Bradley 1989). Several of these strategies have been shown to significantly reduce damage by cotton pests.

Strip harvesting

The management program developed for *Lygus hesperus* in the San Joaquin Valley of California (Stern et al. 1964, 1967) provides an excellent example of the fact that management practices on one crop may profoundly influence pest damage on another. These authors noted that conventional harvesting of alfalfa, the preferred host of *Lygus* in California, was usually followed by a mass influx of the pest into cotton. By harvesting alfalfa in strips, rather than entire fields, *Lygus* infestations remained largely concentrated on alfalfa and the need for insecticidal treatment on cotton was greatly reduced (Stern et al. 1964, 1967, Reynolds et al. 1975).

Strip-cropping

Laster (1974) defined strip-cropping as "the interplanting of primary crops with uniform parallel strips of secondary crops in sufficient density to harbor ample beneficial insect populations to combat insect pests of the primary crop." Interplanting of alfalfa and cotton in California achieved a twofold effect: *Lygus hesperus* preferentially infested alfalfa (as long as the latter remained lush) and densities of certain natural enemy species increased substantially (Stern 1969). Similar natural enemy increases were evident in Oklahoma cotton fields interplanted with sorghum (Robinson et al. 1972, Burleigh et al. 1973, Johnson et al. 1976), which has been formally recommended as a control strategy for that area (Coakley and Young 1975). Pierce et al. (1912) recommended the planting of certain cultivated crops (e.g., cowpeas) and native vegetation (e.g., dewberries) in close proximity to cotton as a means to generate field nurseries of boll weevil parasites. The latter strategy, while conceptually sound, has not been tested empirically or adopted.

Provision of Supplemental Nutrients

Since commercial cotton cultivars (e.g., nectariless cottons) may be deficient in nectar sources required by certain types of natural enemies, several strategies have been proposed to supply such resources artificially (see review in Johnson et al. 1986). Certain types of native vegetation may provide such nutrients (King and Holloway 1930), although it should be recognized that these same species may conceivably harbor important plant pathogens (van Emden 1965).

The application of artificial honeydew, a mixture of sugar and Wheat (Hagen et al. 1976), has been shown to attract and increase oviposition of a number of important predators (Hagen and Tassan 1970, Hagen et al. 1971). Application of artificial honeydew resulted in a 3-fold increase in oviposition by *Chrysoperla* (= *Chrysopa*) and a significant reduction in bollworm damage to cotton (Hagen et al. 1971). A similar effect was documented in Arkansas, where application of a sugar-Wheat mixture to cotton was accompanied by a one-month delay in the need for insecticidal treatment for bollworm on cotton (Denver 1974).

Weed Management

The significance of wild hosts in the seasonal population dynamics of highly polyphagous cotton pests is somewhat conjectural and appears to vary regionally (Stadelbacher et al. 1986). Surveys in certain areas e.g., southern Texas (Harding 1976), have suggested only moderate densities of *Heliothis* and *Helicoverpa* on native hosts during the early-spring period, while major concentrations of both pest species have been documented on plants such as crimson clover, *Trifolium incarnatum* L., and Carolina geranium, *Geranium carolinianum* L., in other areas, e.g., the southeastern states (Snow and Brazzel 1965, Snow et al. 1966). Stadelbacher (1982) demonstrated that bollworm densities on *Geranium dissectum* L. could be reduced by ca. 95.9 percent by a single properly-scheduled mowing, and by ca. 99.6 percent by a single herbicide application. Knipling and Stadelbacher (1983) noted that bollworm infestations on wild hosts during the early-season period tend to be concentrated within a relatively restricted area, and projected that 90 percent control of reproduction by first-generation bollworms on such hosts might be obtained through mowing, cultivation and application of selective herbicides. Destruction of weeds such as *Croton* spp. has also been proposed as a means to control cotton fleahopper (Reinhard 1926, Eddy 1927, Folsom 1932), although the efficacy of this approach has not been demonstrated (Sterling et al. 1989).

Three possible adverse effects of weed management should be recognized: stands of native vegetation may be important aesthetically and/or for erosion control, may constitute important reservoirs of natural enemies (Altieri et al. 1977, Altieri and Whitcomb 1979, King et al. 1982) and may also serve as important food sources for wildlife (Sterling et al. 1989).

Destruction or Modification of Overwintering Sites

In contrast to the majority of serious cotton pests, diapausing adult boll weevils (particularly in temperate environments) overwinter in a state of dormancy in certain types of preferred habitat, the most important of which is deciduous leaf litter (Bottrell et al. 1972). Isely (1930) conducted a brush-clearing experiment in a 600-acre tract in Arkansas, and documented a substantial decline in boll weevil damage during the following season. More recently, Slosser and Boring (1980) studied the effects of pruning or thinning trees in "shelter-belts" (rows of trees planted during the 1930s for erosion control) and documented a significant reduction in overwinter survival of boll weevil which they attributed to this type of "shelter-belt management."

Cultural Controls and Pest Population Management

Many of the cultural strategies discussed previously are singularly effective against one or more cotton insect or disease pests. Most become considerably more effective when used in combination with other cultural strategies, and may become particularly potent when applied in combination with other strategies in an organized community-wide pest management effort. The current trend towards management of pest populations through a regional, rather than field-by-field, approach has long been advocated (Knippling 1979) and ranks among the most significant changes in the philosophy of pest management which have occurred during the present century.

Regional Pest Control Programs

During the past two decades, regional control programs for cotton pests have been implemented in several areas of the United States (Henneberry et al., in press). The more important of these include the *Heliothis* Management Program in Arkansas (Phillips and Nicholson 1979) and several management or eradication programs for boll weevil (Davich 1976, Andrews 1981, Hamer et al. 1983, Masud et al. 1984, Farr and Lane 1987, Summy et al. 1988a, Brazzel 1989). Operational differences notwithstanding, these programs share one common denominator, i.e., the objective of obtaining effective control through an organized and concerted attack on the pest population, rather than individual infestations.

A Case Study: the Lower Rio Grande Valley of Texas

One of the most recent regional management programs for cotton pests was directed against boll weevil in the Lower Rio Grande Valley (LRGV) of Texas (Summy et al. 1988a). Many aspects of the LRGV program are unique to the subtropical south Texas environment; however, others (particular the logistical difficulties involved) are likely to be encountered in similar programs established in environments ranging from tropical to temperate. The LRGV region encompasses a four-county area in extreme southern Texas and an equivalent area of northern Tamaulipas, Mexico. Cotton has traditionally ranked among the principal and most profitable agricultural crops of the LRGV region, although problems with insect pests have been among the most severe in the Nation. Outbreaks of organophosphate-resistant tobacco budworms during the early 1970s caused unprecedented damage to LRGV cotton and destroyed the 275,000-ha cotton industry of northern Tamaulipas, Mexico, within a period of ca. three years (Reynolds et al. 1975). These disasters, more than any encountered previously, emphasized the dangers of unilateral reliance on insecticides and the need for ecologically-sound management practices for cotton pests.

The rejuvenation of LRGV cotton production may be attributed in part to the development of a "short-season" production scheme, which required nearly two decades of research and involved the merger of several important cultural strategies (Namken and Heilman 1973, Larson et al. 1975, Namken et al. 1975, 1979, Gausman et al. 1979, Heilman 1987, Heilman et al. 1979, Namken et al. 1983). Namken et al. (1983) outlined the salient features of short-season cotton production in areas such as the LRGV: 1) the use of rapidly-maturing cultivars in combination with early-season insecticidal treatment to minimize damage by overwintered boll weevils, and 2) incorporation of agronomic practices designed to hasten crop maturity and thus evade much of the late-season "*Heliothis*" infestation. The transition from indeterminate to determinate cotton cultivars (Bird 1976) proceeded at a somewhat slower pace than in other areas of Texas because of initial problems with fiber quality with the new short-season types. However, once these problems were resolved, the transition proceeded rapidly and virtually all cotton currently produced in the LRGV region is classified as "short-season" (Heilman 1987).

A second major development in cotton pest management involved the implementation of a regional stalk destruction program directed primarily against boll weevil (Summy et al. 1988a). Contrary to popular opinion, stalk destruction in much of south Texas (the LRGV in particular) has, until recently, been largely a matter of rhetoric rather than one of concerted action. For several decades previously, the Texas Pink Bollworm Quarantine provided a legal basis for mandatory stalk destruction, but was fraught with legal technicalities (for example, the absence of any provisions for control of boll weevil) and was only rarely enforced effectively. Mandatory stalk destruction was strongly reemphasized following a series of destructive boll weevil outbreaks during the late 1970s and early 1980s, and (after the limitations of the Pink Bollworm Quarantine became evident) a decision was eventually made by the local cotton industry to pursue entirely new legislation. During 1987, the Texas Legislature enacted the Texas Boll Weevil Control Act, which provides stringent regulations on early stalk destruction and, in contrast to previous legislation, holds producers and landowners jointly liable for stalk destruction violations. Under provisions of the new legislation, pest management zones for control of boll weevil have been implemented in 31 south and west Texas counties (Summy et al. 1988a). Regulations applicable to the LRGV region originally established a stalk destruction deadline of 15 September, which has more recently been reverted to 1 September.

Despite the relatively simple rationale of early stalk destruction, i.e., as a means to curtail or eliminate boll weevil reproduction and overwintering via diapause or survival in desiccated bolls (Summy et al. 1988a), logistical difficulties involved in the implementation of a regional stalk destruction program proved to be formidable (Summy et al. 1989). One of the principal problems involved detection of undestroyed cotton, a significant fraction of which commonly occurred in relatively isolated sites inaccessible by public roads. A second problem involved delays in stalk destruction due to inclement conditions, e.g., precipitation, which tends to increase substantially during September, and soil compaction, which may preclude plowing by conventional implements. Such delays were almost invariably accompanied by lush growth of cotton plants (volunteer and regrowth) and the development of dense weevil infestations which generally proved to be difficult, if not impossible, to destroy during the fall and winter period (Summy et al. 1988a). These problems were addressed by the development of an aerial surveillance

system to facilitate efficient detection of cotton (Summy et al. 1984, 1988a) and several strategies to ameliorate the effects of inclement conditions (Summy et al. 1986a, 1986b). Problems with the small minority of producers who, through ignorance or apathy, simply refused to abide by stalk destruction guidelines was effectively addressed by the new stalk destruction legislation.

The merger of rapidly-maturing cotton cultivars and early stalk destruction into a single "short-season" production system completed the scheme of cultural controls recommended by cotton entomologists nearly a century ago (e.g., Howard 1896). The effect has been a significant reduction in boll weevil damage and a concomitant reduction in insecticide usage on cotton. Summy et al. (1988a) noted that a series of destructive boll weevil outbreaks during the late 1970s and early 1980s (which were largely the result of lax stalk destruction) caused significant yield reductions and a substantial increase in insecticide usage on LRGV cotton. For example, production data for irrigated cotton during 1980 indicated an average yield of ca. 400 lbs/ac and an average number of insecticide treatments approaching 15.0, a figure comparable to that documented during the earlier tobacco budworm outbreaks (Reynolds et al. 1975). During a brief period in which the degree of stalk destruction became increasingly efficient, average yields increased while insecticide usage declined appreciably (e.g., by 1984, average yields had increased to ca. 766 lbs lint/ac while the average number of insecticide treatments to irrigated cotton had declined to ca. 6.5). Conversely, such trends were reversed entirely during a period in which stalk destruction became increasingly lax (e.g., by 1986, average yields had declined to ca. 605 lbs lint/ac while insecticide treatments had increased to ca. 11.0). With the advent of new stalk destruction legislation during 1988, and renewed emphasis by the regulatory agency charged with enforcement, the average number of required insecticide applications declined appreciably, e.g., to 5-6 for irrigated and <1.0 for dry land cotton during 1990 (J. W. Norman, Texas Agricultural Extension Service, pers. comm.).

The latter trend is particularly timely as a means to lessen selection pressure on the local population of boll weevil, which appears to be considerably less susceptible to azinphosmethyl than other populations in Texas (Teague et al. 1983), and tobacco budworm, which has recently exhibited evidence of resistance to two of the synthetic pyrethroid insecticides (Plapp and Campanhola 1986, Roush and Luttrell 1987). Moreover, the reduction of

pesticide usage on LRGV cotton has created an environment more conducive to the utilization of biological control agents for cotton pests and has fostered an unusual degree of cooperation between LRGV cotton producers and local environmentalists (Graham 1990). The latter trend stands in marked contrast to the controversies which characterized boll weevil control and eradication efforts in other areas of the United States during recent years.

Much of the technology employed during the stalk destruction effort has much broader applications in agriculture. For example, the color infrared photography used in aerial surveillance has been used extensively to estimate crop yields (Thomas and Oerther 1977), evaluate the effects of nutrient stress and freeze damage (Escobar et al. 1983, Thomas and Leamer 1987), and to assess damage caused by insect and disease pests (Norman and Fritz 1965, Hart and Meyers 1968, Heald et al. 1972, Hart et al. 1977, Manzer and Cooper 1982, Wildman 1984). In conjunction with more recent innovations such as color video imagery (Nixon et al. 1987) and satellite imagery (Richardson et al. 1989), such remote sensing technology forms the basis for the development of a Geographic Information System for the LRGV and other areas (J. R. Richardson, pers. comm.). Perhaps the most significant result of the stalk destruction effort has been acceptance by the majority of LRGV producers of the need for regional management of boll weevil and other cotton pests. The concept of regional management has more recently been extended to the newly-emerging cotton industry of Tamaulipas, Mexico, which has escalated from ca. 1,200-ha during 1989 to ca. 60,000-ha during 1991. Several recent meetings between cotton producers from Texas and Mexico stressed the theme that effective management of boll weevil in the LRGV region will be possible only through a sustained cooperative effort involving both countries. As a result, stringent stalk destruction regulations have been reinstituted in northern Mexico, although a cooperative management program with the United States has yet to evolve.

To summarize, the current management program for LRGV cotton pests involves an array of cultural strategies which have been voluntarily adopted as part of the changing technology of cotton production (e.g., determinate cotton cultivars, plant growth regulators and defoliant or desiccants) and others which have been mandated by law (e.g., planting and stalk destruction deadlines). Many of the important cultural strategies discussed herein have received

little emphasis (e.g., minimizing rates of irrigation and fertilization) but could greatly increase efficacy of the overall program if adopted by the majority of producers.

Summary

Cotton production in the United States during the past two decades has shifted largely from production systems heavily dependent on broad-spectrum insecticides to systems utilizing an array of ecologically-sound cultural and biological controls. Widespread adoption of cultural strategies, which range from use of resistant cultivars to a sequence of agronomic practices which render the environment less hospitable to one or more pests, has greatly diminished damage by key pests, reduced the incidence of secondary outbreaks, and is expected to create an environment conducive to the success of additional strategies such as biological control. Cultural strategies become particularly potent when incorporated into organized regional pest management efforts, and provide a means to produce cotton profitably without the serious economic losses and environmental degradation which has characterized cotton production in the past.

Acknowledgment

The authors express appreciation to Drs. T. J. Henneberry, T. F. Leigh and J. K. Walker for critical reviews of this manuscript.

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The Problem of Cotton Pest Resistance to Pesticides in the former Union of Soviet Socialist Republics and Rational Systems to Cope with this Phenomenon

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Cotton is the first crop in the former Soviet Union on which resistant pest populations have emerged and caused serious economical losses. The importance of resistance for this crop is therefore obvious.

The first reports on the emergence of resistance on cotton appeared in the early sixties when resistance to metasystox in populations of the two-spotted spider mite, *Tetranychus urticae* Koch, was noted in the Yangiulsky region of Uzbekistan (Ivanova and Kornilov 1964). However, in 1965, observations of resistance in cotton-growing regions of the Republic revealed a 350-fold level in Fergana valley (Zainutdinova and Slivochkina 1968). The reports on losses in efficiency of organophosphates (OPhs) not only in Uzbekistan but also in some regions of South Tajikistan occurred during this period (Manina 1968; Smirnova 1968). In the latter case, 200-500-fold levels of resistance to metasystox, intration, kilval and other chemicals were shown (Smirnova et al. 1971).

In the early seventies a substantial increase in the resistant area of *Tetranychus urticae* to OPhs was observed in regions sustaining intensive application in Uzbekistan and Tajikistan. Simultaneously, however, the susceptibility of *T. urticae* to this group of toxicants was maintained in areas with moderate number of pests and low number of applications of OPhs (in several districts of the Northern Uzbekistan, Central Tajikistan, and Azerbaijan) (Smirnova et al. 1972).

In the late sixties and early seventies, the All-Union Institute for Plant Protection (VIZR) devised a rotation of specific contact acaricides (kelthane, neoron, tedion, acrex and milbex) that not only prevented economical loss in regions with maximum resistance, but also retarded the spread of resistance into safer regions. The tactic of acaricide application has also changed from aerial treatments with systemic compounds to ground treatments with contact chemicals by means of a ventilator apparatus. This permits treatments of fields on the basis of economical thresholds thereby markedly decreasing the number of applications of highly-toxic pesticides (Smirnova et al. 1975).

The substantial decrease in the usage of OPhs for controlling *Tetranychus urticae* in South Tajikistan has considerably delayed the development of resistance to these chemicals in populations of *Aphis gossypii* Glov. and *Acyrtosiphon gossypii* Mordv., though an initial stage of its forming to metasystox and rogor in the early seventies in the Kulyab region (Ivanova 1975). However, in the early eighties, the emergence of aphid populations resistant to these chemicals was observed in the regions of Central Tajikistan (Kovalenkov 1984). The high levels of resistance (200-fold) to OPhs in cotton aphid populations in the Tashkent region of Uzbekistan and their cross-resistance to the carbamate, pirimor, was noted in the same period (Hodjayer et al. 1985). An unprecedented outbreak in cotton aphid reproduction was observed that year in the farms of South Tajikistan due to intensive use of rogor and pyrethroids. As a result, at the end of season in the Parhar region we found 500-fold level of cotton aphid resistance to rogor, 67-fold level to phosalone and the development of cross-resistance to the pyrethroids permethrin, cypermethrin and fenvalerate. The latter were used during some years against the other key pest, the cotton bollworm, *Helicoverpa armigera* Hübner, in this region.

Resistance in populations of the bollworm, *H. armigera*, has been the slowest to appear because of its development on a number of crops in addition to cotton (chick pea, tomato, corn, potato and alfalfa) which are seldom, if ever, treated with chemicals in the former U.S.S.R. As a result, only a part of its population is treated with insecticides. Moreover, only one or two generations from 3-5 are subject to intensive treatments, depending on the region and weather conditions. All this affects selection rate of resistant genotypes in populations of this insect and retards the development of its resistance compared to other pests. Resistance of the bollworm, to DDT compounds was experimentally produced in the early seventies in Azerbaijan (Ragimov et al. 1975) and in South Tajikistan (Smirnova et al. 1972). In the middle of the 1970s, cross resistance to polydophene, polychlorcamphene and dilor was recorded in the same regions which coincided with a sharp decrease in the effectiveness of organochlorine compounds in the control of the same insect (Sukhoruchenko 1976). In 1977 the 97-fold level of resistance of this pest to DDT and the complete loss of effectiveness of this insecticide were noted in the Parhar region. It was also discovered that this population was resistant to sevin (32-fold index) and tolerant to phosalone (Sukhoruchenko et al. 1980). At the same time, data in

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Azerbaijan (Muganskaya region) indicated a considerable decrease in effectiveness of sevin (Agaeva and Babaeva 1980). Thus, in the late seventies and in the early eighties the populations of cotton pests in the former U.S.S.R. were at different stages of development of resistance to pesticides used (Table 1). In some cases, high levels of resistance were noted, and as a result, whole groups of pesticides were lost in practice (e.g., OPhs toward spider mites and organochlorine insecticides toward the bollworm). In other cases tolerance was observed (bollworm to sevin and phosalone; cotton aphids to organophosphates) when insect pests responded to pesticide treatments, but this effectiveness was lost rapidly due to increasing levels of resistance.

Duration and intensity of pesticide application had a large influence on population development in beneficial insects. In this connection, the most difficult situation concerning resistance was in cotton-growing areas where the optimum combination of factors favored increase in the numbers of pests, and accordingly, increase in pesticide treatments was observed. The South Tajikistan is one of these regions where populations of *T. urticae*, *H. armigera*, *A. gossypii* and *Ac. gossypii* were found resistant because VIZR chose this region to develop a system for delaying development of resistance in populations of several pest species simultaneously. Complicating this system was the fact that ways to cope with resistance in separate pest species had to be combined in such a way in order to prevent resistance in the whole complex of arthropoda.

In keeping with the idea that resistance is a microevolutionary phenomenon based on genotypical changes in populations under selective pressure of pesticides, the best strategy to cope with resistance is management by decreasing the toxic pressure on the agrobiocenosis of cotton fields.

The second strategic principle based for this system is management of resistance by noting all positive and negative sides of pesticide effects on populations of noxious and beneficial arthropods in cotton fields. Most attention must be paid to the preservation of natural beneficial entomofauna that under conditions of less pesticide pressure would contribute to the reversion of resistance by killing resistant individuals. We can also combine efficiency of chemical control with pesticide aftereffects resulting in less toxic pressure on agrobiocenoses.

Based on these strategies, an integrated resistance management program has been developed by rotating pesticides based on modes of action. Pesticides have been chosen for rotation based on the spectrum of cross-resistance and its possible outcomes. Pesticides from seven chemical groups have been chosen: organophosphates, organochlorine compounds, carbamates, pyrethroids, and nitrogen-tin-sulphur-containing compounds. These are acaricides: kelthane, neoron, mitran, acrex (isophen), omite, plictran, sulphur; and the insecticides rogor, phosalone, pirimor, gardona, dilor, thiodan, etaphos, sevin, kroneton, ambush, corsar, rovicurt, ripcord, cymbush, sherpa, decis, sumicidin. Viral (elcar, virin-XS) and biological preparations (dendrobacillin, bitoxibacillin) have been included in the control program as alternative agents to reduce toxic pressure. The use of every pesticide in the rotation program was based on economic thresholds and with constant monitoring of the development of resistance to pesticides in populations of major pest species.

The need for preservation of beneficial insects was taken into account while working out the seasonal control program. An index was developed which showed not only the initial toxicity of pesticides but also the recovery rate of beneficial species in treated fields. After long-term studies, the following toxicity classes to define the hazard rating associated with the use of pesticides for beneficial entomofauna have been established:

- first class - slightly toxic pesticides cause 20% decrease in numbers of populations - 10 days after treatment under field conditions;
- second class - moderately toxic pesticides - cause 21-50% decrease in numbers of populations 10 days after treatment;
- third class - highly toxic pesticides - cause more than 50% decrease in populations 20 days after treatment.

Pesticides selected for rotation on the basis of the toxicity rating are classified in the following way (Table 2):

- sevin, rogor and pyrethroids belong to the class which is dangerous for entomophages despite a slight toxicity for some species;

- gardona, phosalone, thiodan and pirimor belong to the class of pesticides which are moderately toxic for zoophages;
- dilor and croneton are the safest insecticides, which are similar in accord with the toxicity rating to specific acaricides: kelthane, milbex and biopreparations which belong to the slightly toxic class.

The ability of broad-spectrum insecticides to stimulate the development of sucking phytophages, especially the spider mite, has also been taken into consideration (Fig. 1).

The characteristics of a given pesticide selected for rotation were used to determine its place in seasonal control programs. Thus, pesticides slightly toxic or moderately toxic to zoophages which do not cause an increase in number of sucking pests (microbiopreparations, phosalone, dilor, thiodan, croneton) may be used for the first half of the season (up to the middle of July). For the second part of the season (from the middle of July to the end of August) more toxic pesticides may be used which may result in the increase in populations of sucking species. Specific acaricides may be safely used for agrocenosis during the entire vegetative period.

The position in rotation of insecticides used against the bollworm is determined by their rate of their inhibiting action on pest populations. The marked reduction of population indices in survival of preimaginal stages, net reproductive rate, biotic potential, etc., from usage of thiodan and pyrethroids compared to gardona and phosalone as treated in filial generations (Table 3 - example with thiodan, phosalone and gardone) has shown a need to use these materials during maximum concentration of the bollworm in cotton. This time coincides with the development of second generation of the pest, and a reduction of the number of insecticide treatments in the third generation will follow.

Six-years of using rotation schedules based on the above-mentioned approaches have shown that a high protective effect may be achieved if rogor and phosalone are rotated with any specific acaricide in zones where spider mites are not resistant to organophosphates. Organohaloid compounds (kelthane, neoron, mitran) are rotated with members from nitrogen-sulphur tin-containing groups (acrex, omite, plictran, sulphur compounds) in zones where spider mites are resistant to organophosphates. Organophosphates (gardona, phosalone) should be rotated with biopreparations

(dendrobacillin, bitoxibacillin, elcar, virin-XS) in the first generation of bollworm, chemicals of diene synthesis or pyrethroids in the second generation, and carbamate sevin in the third generation. However, gardona, phosalone, and dilor are not used in regions where an insect pest is resistant to organophosphorus or organochlorine insecticides. Any compounds from organophosphates or carbamates may be used for controlling aphids in regions where resistance is not observed. Rotation of etaphos and phosalone with pyrethroids is recommended in areas where resistance is known.

The main positive effect in the use of resistance management programs is reducing or inhibiting the development of resistance to pesticides. For almost 10-years of rotation, resistance to rogor in spider mites has been reduced nearly 10 times; phosalone, kelthane, acrex and omite remain effective at the same dose; usage of plictran has increased by 14.5 times, but its effectiveness has not been reduced (Table 3). The sensitivity of *Acyrtosiphon gossypii* to aphicides remains at the same level (Table 3). However, an increase in resistance of *Aphis gossypii* to phosalone and rogor has been observed, but the efficiency is not decreasing under these indices. Resistance to DDT in the bollworm was reduced from 97- to 7-fold level, and resistance to sevin - from 29.9 - to 0.7 level. Resistance to phosalone has remained the same, and sensitivity to pyrethroids in bollworm populations has decreased similarly to DDT.

The decrease in indices of resistance to pesticides applied in pest populations has shown a remarkable turnaround within ten years. It has resulted in the reduction of toxic pressure on agrobiocenosis to an extent that beneficial arthropods have recovered in high enough numbers to aid in control of pests. Numbers of treatments per season using resistance management has been no more than five during years with low populations of the pest.

These positive aspects of insecticide control improve the economic situation. The average annual benefit has been 59.84 rbl/ha increase through resistance management. In 1984 this program was approved by the Scientific and Technical Council of the Ministry of Agriculture in the former U.S.S.R. In 1985, "Recommendations on rational rotations of insecticides, acaricides and biopreparations in control of resistant populations of cotton pests" was published. From 1985 until 1988 the rotation of pesticides was introduced in farms of South Tajikistan on the area of 75,000 hectares of cotton.

In addition to an educational program, providing adequate pesticides is necessary for the program to work. However, the plan worked out 10 years ago has undergone substantial changes. Acrex, pirimor and sevin were banned from use because of environmental considerations. Thiodan may be banned for the same reasons; thus, we must search for efficacious alternatives.

The intensive use of organophosphates and pyrethroids for the control of the bollworm in 1989 resulted in the high levels of resistance to rogor and cross-resistance to some pyrethroids. Thus, it is also necessary to search out aphicides among pesticides from other groups including microbiopreparations; good results were obtained with pegas - a member of the thiourea. The field bug *Lygus pratensis* L. is a problem at present time and biopreparations are being tested for this insect as substitute insecticides; dipel, legend, and aim are examples of products of interest for resistance management of the bollworm.

Because emphasis has been placed on the usage of pyrethroids with acaricidal activity (e.g., danitol, mavric, and rufast), resistance management programs have changed considerably these past years. We feel that in the future this program will improve as advancements in biological control are made. Knowledge of physiological, biochemical and genetic mechanisms of resistance will be the basis for more fundamental changes in similar control programs.

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Table 1. Reversion and retarding the resistance in cotton pest populations after rotation of pesticides

Pest	Pesticide	Levels of resistance	
		1977-1978	1986-1987
<i>Tetranychus urticae</i>	Rogor	250.0	21.0
	Phosalone	39.0	20.0
	Kelthane	22.0	32.0
	Acres	4.3	2.3
	Omite	4.0	0.7
	Plictran	1.7	14.5
<i>Aphis gossypii</i>	Rogor	0.5	5.7
	Phosalone	3.4	22.0
	Kroneton	1.3	1.0
	Pirimor	1.0	1.0
<i>Acyrtosiphon gossypii</i>	Rogor	3.5	3.6
	Phosalone	8.5	8.5
	Kroneton	1.0	1.0
<i>Helicoverpa armigera</i>	DDT	97.3	7.0
	Sevin	29.9	0.7
	Phosalone	4.0	5.4
	Gardona	1.0	1.2
	Thiodan	1.0	2.0
	Ambush	1.0	0.1
	Decis	1.0	0.1
	Gymbush	1.0	0.1
	Sumicidin	1.0	0.3

Table 2. The degree of hazard of pesticides to beneficial arthropods

Pesticide	Classes of hazard for								
	<i>Adonia variegata</i>	<i>Orius niger</i>	<i>Nabis palifer</i>	<i>Deraeocoris punctulatus</i>	<i>Aeolothrips intermedius</i>	<i>Chrysoperla carnea</i>	<i>Araneina</i> sp.	<i>Trichogramma evanescens</i>	zoophages
Rogor	3	2	3	3	3	3	1	3	2.6
Phosalone	1	2	2	2	3	2	1	0	1.8
Gardona	3	1	1	2	3	0	1	0	1.4
Dilor	1	1	1	1	1	0	1	0	0.8
Thiodan	3	0	3	2	3	1	2	1	1.8
Kelthane	2	0	0	0	0	0	0	1	0.6
Milbex	1	0	2	0	0	2	1	1	0.9
Sevin	3	3	3	3	3	2	3	3	2.9
Kroneton	0	1	1	2	1	1	0	2	1.0
Pirimor	1	2	1	2	2	2	2	2	1.8
Ambush	3	2	3	2	3	3	3	2	2.6
Cymbush	3	2	3	1	3	2	3	3	2.5
Decis	3	2	3	2	3	3	3	3	2.8
Sumicidin	3	2	3	2	3	1	3	3	2.5
Biopreparations	3	1	2	0	0	2	2	0	1.3

Table 3. Demographic characteristics of a population of *H. armigera* untreated and treated by insecticides.

Pesticide	Generation	Population Parameters		
		R_0	T	r_m
Thiodan	II	9.32	44.5	0.0503
	III ¹	0.00	0.0	0.0000
Untreated	II	37.30	33.5	0.1090
	III ¹	51.58	41.4	0.0950
Phosalone	I	27.23	41.3	0.0818
	II ¹	2.24	43.5	0.0190
Untreated	I	99.78	41.7	0.1111
	II ¹	2.67	46.4	0.0250
Gardona	I	95.94	39.4	0.1168
	II ¹	24.98	34.5	0.0935
Untreated	I	101.40	36.3	0.1261
	II ¹	102.71	34.2	0.1362

¹ Daughter generation

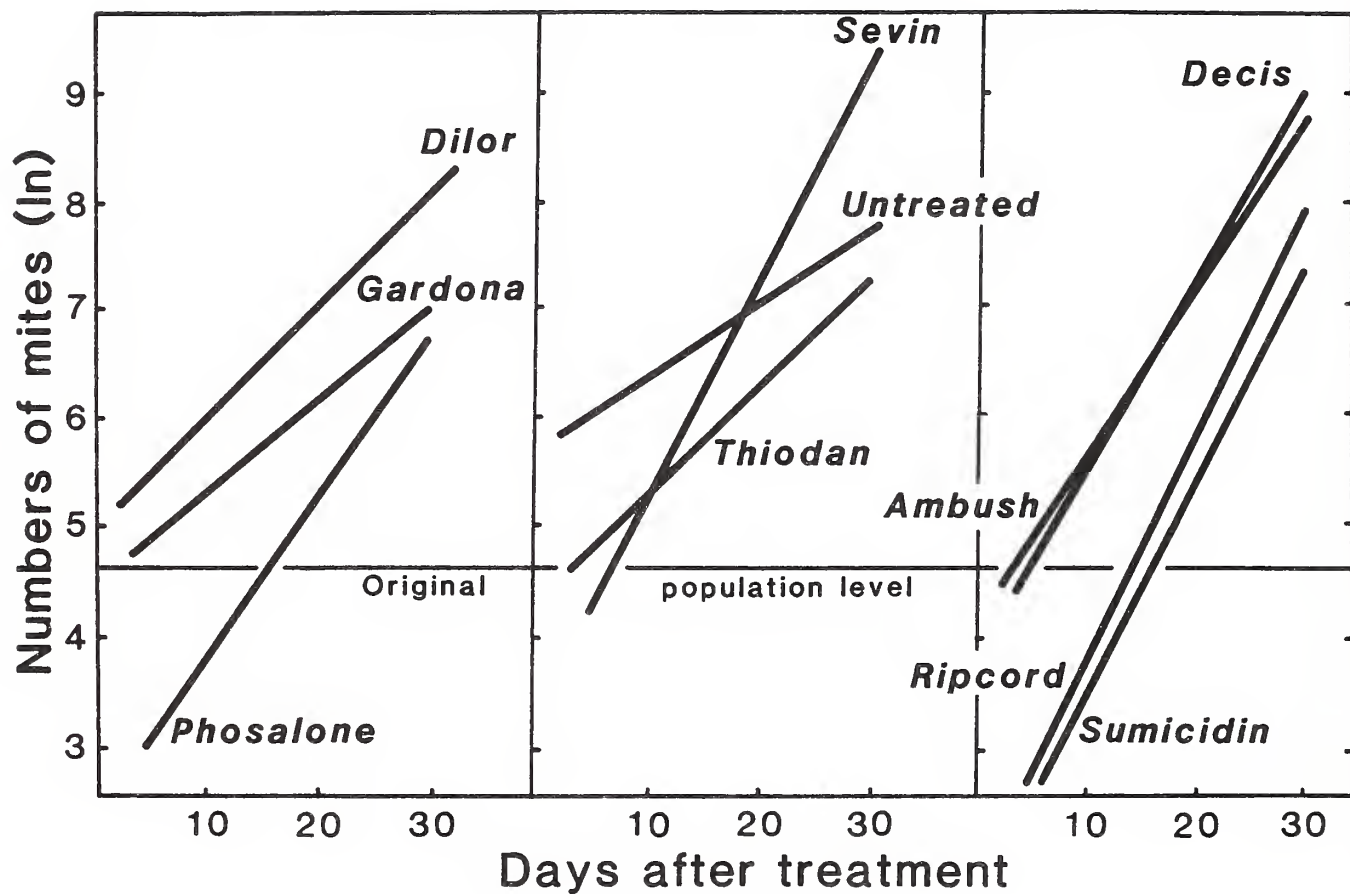


Fig. 1. The dynamics of two spotted spider mite through insecticide treatments. Numbers on the y-axis are changes in population sizes (in natural logarithms) compared with the initial size.

Prospects and Status for Development of Novel Chemicals for Integrated Pest Management in Cotton

Julius J. Menn¹

Abstract

Increasing concerns regarding food and feed safety, quality of groundwater and surface water, and resistance of insects to chemical pesticides have provided added impetus to the development of integrated pest management (IPM) systems for cotton. The chemical industry is cognizant of these concerns and is directing increasing research resources to develop more selective, IPM-compatible pesticides through more rational approaches than those used previously. This paper discusses the status of current chemical control practices in cotton and describes several promising candidate control agents that would be compatible with IPM. The developing use of semiochemicals for insect control is also briefly discussed in terms of the potential of the IPM approach to reduce the application volume and frequency of conventional insecticides.

Introduction

Corn, soybeans, cotton, and cereals constitute the most important crop plants in the United States. The Economic Research Service (ERS) of the U.S. Department of Agriculture (USDA) forecasted that approximately 5.5 million hectares (ha) would be planted to cotton in the United States in 1990 (ERS 1990).

Of the 64 million pounds of insecticides used on major field crops in 1990 in the United States, 19 million pounds, or 30 percent was applied on cotton (ERS 1990). The latter figure translates to 1.5 kg of active ingredient per hectare (ha). Synthetic pyrethroids (SP's) constitute about one-half the volume of all insecticides applied on cotton, and their application rates are low, ranging from 0.02 to 0.22 kg/ha (Menn et al. 1989). This high use of SP's on cotton assumes even greater significance, considering that in some parts of the Cotton Belt, especially in the Southeast, they may be applied as many as 10 times per growing season. The primary targets of these applications in order of importance are the boll weevil [*Anthonomus grandis* Boheman] and the "Heliothis" complex, which

comprises the tobacco budworm [*Heliothis virescens* (Fabricius)] and the bollworm [*Helicoverpa* (*Heliothis*) *zea* (Boddie)].

Despite intensive efforts in the integrated pest management (IPM) arena (Frisbie 1985), heavy pesticide use in cotton still continues. Perhaps the greatest difficulty in developing IPM strategies that incorporate the use of conventional chemicals is rooted in the great diversity of cotton insect pests. These include not only the boll weevil and "Heliothis" complex but also intermediary and more regional pest species, such as the sweet potato white fly [*Bemisia tabaci* (Gennadius)], *Lygus* species, including the tarnished plant bug [*Lygus lineolaris* (Palisot de Beauvois)], the pink bollworm [*Pectinophora gossypiella* (Saunders)], and spider mites. Complicating IPM efforts is the ability of the "Heliothis" complex to migrate long distances and the invasion of pest species from other croppings. The chemical industry, the major discoverer and developer of chemical insecticides, has long recognized cotton as a primary target for field testing new insecticides. In fact, many insecticides in the United States were first registered for use on cotton, due to the diversity of insect pests and relative ease of registration. However, because cottonseed oil is classified as a raw agricultural food commodity, registration can be more readily obtained for insecticides to be used at the preflowering stage of cotton than for those to be used at later stages. Developing first prebloom uses would avoid the need for extensive compilation of data on residue in cottonseed oil. Such a compilation is required for full tolerance registration by the U.S. Environmental Protection Agency (EPA).

Current Chemical Control in Cotton

An estimated 35 chemical insecticides are in current use to control various pests of cotton in the United States (Suguiyama and Osteen 1988). The insecticides in greatest use, based on 1988 data, are shown in Figure 1. Parathion (22.7%), methyl parathion (10.7%), azinphos-methyl (4.6%), dicofol (6.4%), acephate (2.6%), and SP's (21%) account for 77.2% of all insecticides applied on cotton (C. Giedraitis, personal communication, 1990).

While the organophosphorus esters (OP's) are still the primary chemical weapons against the boll weevil and sucking insects, the SP's have in recent years become the major weapons against the "Heliothis" complex. The SP's

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appeared to be the ideal insecticides: effective at low rates and yet relatively safe to beneficial insects; fairly nonpersistent in the environment; and low in cost, based on use pattern.

However, as early as 1985-1986, control failures with SP's were reported in Texas (Bull and Menn 1990). It appears now that genes for SP resistance are present in populations of the "Heliothis" complex in the United States, and it is likely that resistance to these insecticides will continue to build as a consequence of intensive use pattern (Bull and Menn 1990). Although the resistance phenomenon portends economic difficulties for cotton production, it may in the long-term catalyze the development of biological control agents and more selective chemical insecticides that can be used in IPM systems for cotton.

Discovery of New Chemical Insecticides

Discovery and successful market introduction of a synthetic chemical pesticide has been likened to the development and successful launching of a spaceship. Both projects are highly creative, interdisciplinary, costly, and unpredictable. In the case of the pesticide, more competition and time are involved due to the uncertainties of the registration process.

Details of the research and development process to bring to market a new pesticide were extensively reviewed in numerous articles, including those by Menn (1983), Braunholtz (1981), and Menn and Henrick (1985).

Table 1 shows the four stages for producing and bringing one successful candidate to market. It had been estimated, based on previous publications (Menn and Henrick 1981; Braunholtz 1981), that only one in 20 thousand synthetic compounds will reach the marketplace. According to R.F. Flattum (personal communication 1990), this ratio has escalated to one in 40 thousand compounds in 1990. In the late 1970s, the activities shown in Table 1 were estimated to cost upward of \$21 million (Menn 1983). These costs have escalated to \$30 to \$50 million in 1990 (Flattum, personal communication, 1990). In addition, the cost of a manufacturing plant would also range from \$20 to \$40 million. Therefore, the total investment in a new insecticide could reach upward of \$70 million with an average elapsed time to market of 96 months. Because of these high

costs and long time span, development of a pesticide is a high-risk venture, and only the large multinational companies can afford to be in this enterprise today.

Due to societal, regulatory, and environmental considerations and pressures, the industry has been emphasizing development of more selective insecticides that harmonize control with relative safety to beneficial insects and other nontarget organisms. Due to these constraints, very few insecticides have appeared on the market in recent years. In fact, in 1990, there is not a single new insecticide undergoing registration review for cotton in the United States.

A cardinal requirement for continued use of existing insecticides or introduction of new compounds is that their direct and/or indirect effect on beneficial insects and mites be determined (Croft and Brown 1975; King 1976; Croft 1990; and Elzen and King 1990).

Laboratory and field evaluations are important for providing information on the overt and latent capability of insecticides to reduce populations of beneficial insects and mites. Metabolic studies are also important, because they can provide information for predicting the potential hazard of an insecticide and/or its metabolites to these beneficial organisms. Krieger et al. (1971) have shown that certain beneficial insects have more limited detoxifying capacity than their lepidopterous hosts. The latter have evolved a greater variety of oxidative, reductive and hydrolytic enzymes capable of processing a much broader array of plant constituents than their parasites and/or predators.

Generally, OP insecticides have taken a heavier toll of beneficial insects than SP's and formamidines. SP's if properly used in late season spare beneficials, since they occur in reduced numbers in late season. Beneficials are of prime importance in the early season, when host populations are still relatively low. Chlordimeform (Galecron) was a particularly useful insecticide and miticide in IPM programs since it is a behavior modifying agent that has an indirect ovicidal and larvicidal action (Hollingworth and Lund 1982). However, chlordimeform was recently deregistered in the United States. Possibly a related compound, amitraz (Mitac, Ovasyn), may replace some of the uses lost to chlordimeform. Amitraz is active against a broad range of spider mites, and against the whitefly [*Bemisia tabaci* (Genn.)]; it is a first-instar larvicide and ovicide against the "Heliothis" complex (Peregrine 1989).

Approaches to Discovery of Selectivity

Most synthetic chemical pesticides were discovered through empirical synthesis coupled with broad-spectrum short-term-exposure screening tests on target insects. Screening tests that include nontarget, beneficial insects and mites are conducted only sparingly in industry, and most of the useful information on the response of beneficials to new insecticides has come from universities and the USDA, Agricultural Research Service (ARS). An example of such information was reported by Plapp and Bull (1978), among others, who showed that SP's were reasonably well tolerated by an important predator of the "Heliothis" complex in cotton. This information was most helpful in developing a midseason to late-season IPM strategy for applying SP's on cotton.

The growing emphasis on selective insect control that is compatible with IPM practices has had a marked impact on the chemical industry. It has strongly influenced research thinking and redirection of resources. As a result, more directed approaches for discovering selective insecticides are being used.

These approaches include (1) the synthesis of highly active analogs of biologically active compounds, the direction of the synthesis being guided by the results of quantitative structure-activity relationship (QSAR) analyses, (2) the discovery of natural-product insecticides and also the synthesis of their highly active analogs, and (3) use of a biorational approach to design and synthesize insecticides. These approaches have been described in detail by Morrod (1981) and Magee et al. (1985).

Directed Synthesis

Once a highly active new class of insecticides appears in the patent literature, intensive efforts usually follow in competing industrial laboratories to synthesize analogs with even greater bioactivity through directed research. A pertinent example is the synthesis of selective chitin-synthesis inhibitors that are analogs of diflubenzuron and other benzoylphenylureas (Verloop and Ferrell 1977) (Figure 2).

Diflubenzuron, an insect growth regulator that interferes with chitin biosynthesis in insects, was introduced by Duphar B. V. in 1973. It eventually found a practical niche in cotton production by controlling the boll weevil

and armyworms. In subsequent years, thousands of analogs were synthesized in industry with varying degrees of efficacy and selectivity. In the 1980s, a new compound that retains the benzoylphenylurea core was introduced by Duphar B. V. under the name Andalin (Figure 2). This compound is also targeted as a cotton insecticide and miticide that is compatible with IPM. It is applied at the rate of 40-50 grams ai/ha.

Another example of directed synthesis involves a new thiourea-derived insecticide and miticide that is active against hemipterous insects in cotton and compatible with IPM. This compound, Diafenthiuron (Figure 3), was introduced by Ciba-Geigy AG. Interestingly, this compound exerts its action via photoconversion in sunlight and metabolism in insects and mites to the more reactive carbodiimide (DFCD). DFCD is more toxic than the parent compound to bulb mites [*Rhizoglyphus echinopus* (Fumouze and Robin)] and two spotted spider mites [*Tetranychus urticae* Koch]. Kadir and Knowles (1990) reported that DFCD was a potent agonist of octopamine-activated adenylate cyclase. Thus, they concluded that DFCD is an octopamine agonist.

Undoubtedly, other new candidate insecticides are being tested worldwide on various crops, including cotton. However, if we exclude SP's, only very few representatives of novel classes of insecticides have been described. Most likely, the paucity in new insecticide discovery is due to increased confidentiality because of patent competition and difficulty in discovering selective, cost-effective insecticides that harmonize with IPM.

Natural Products

Natural products derived primarily from plants and microorganisms have provided a vast storehouse of bioactive substances. However, only a few of these have been developed as agricultural insecticides to date.

Synthetic Pyrethroids

The best known and economically most important compounds based on natural products models are the Synthetic Pyrethroids (SP's): they had their genesis in pyrethrins I and II (Elliott 1989). Elliott and co-workers in England

have shown that the photolabile center of pyrethroids could be chemically modified to form compounds with much greater stability in air and light, but with the same or enhanced high insecticidal activity, especially against lepidopterous larvae. The SP's also displayed low mammalian toxicity and low to moderate toxicity against hemipteran predators, but relatively high toxicity to phytoseiid mites (Croft and Whalon 1982).

Currently, the SP's are the premier cotton insecticides in the world. In 1987, the value of the agricultural SP market reached \$1.5 billion, which represented approximately 25 % of the global sales of insecticides (Morton and Collins 1989). In the United States, the pyrethroids are the dominant group of insecticides registered and used against lepidopterous larvae in cotton, primarily to control the "Heliothis" complex. Currently, ten SP's [bifenthrin, cyfluthrin, cyhalothrin, cypermethrin, esfenvalerate, fenvalerate, flucythrinate, karate (lambda-cyhalothrin), permethrin, and tralomethrin] are recommended for application in midseason to late season. If used according to this schedule, there is a better likelihood to delay the development of resistance to these valuable insecticides and protect beneficial insects in the early season (Bull and Menn 1990; Elzen and King 1990).

Avermectin Insecticides and Miticides

The avermectins are a novel class of lactones that are natural products derived by fermentation of the soil microorganism *Streptomyces avermitilis*. The discovery of these microbial products was reported by Campbell et al. (1984). Members of these macrocyclic lactones were shown to possess outstanding anthelmintic (ivermectin) and insecticidal and miticidal activities (abamectin).

The mode of action of the avermectins is different from that of most other insecticides, including the OP's, carbamates, and the SP's. The avermectins are gamma-amino-butyric acid (GABA) agonists that cause paralysis by inhibiting signal transmission at the neuromuscular junction and potentiating a GABA-like action on the GABA receptor/chloride ion channel complex (Campbell 1981). Interaction with the GABA receptor is thought to be a major component of the mode of action of these compounds. However, other potential sites of action are currently being investigated. The avermectins are biologically active in all organisms having a gabaergic system. Selectivity and

differential toxicity of these compounds are a function of uptake, differential metabolism, and mode of delivery. The structures of avermectin B1 (abamectin) and an analog, EMA (MK-243) are shown in Figure 4. Abamectin consists of approximately 80% of component a, where $R = C_2H_5$, and 20% of component b, where $R = CH_3$. Abamectin is primarily a broad-spectrum miticide, providing long residual control of spider mites on cotton. The miticide is active through translaminar foliar uptake. It disappears rapidly from the surface of cotton leaves but is retained in the epidermal cells, the feeding site of spider mites. Because of this translocation, abamectin is relatively nontoxic to predators and parasites and fits well in IPM programs. In field trials, mite control and yields were considerably better in cotton fields treated with abamectin than with dicofol or comite.

In the course of chemical modification studies on abamectin to optimize activity against lepidopterous larvae, it was discovered that substituting an amino group for an OH moiety at the 4"-position in the terminal disaccharide moiety of abamectin (Figure 4) produced a remarkable increase in selective toxicity against major lepidopterous larval pests of cotton (Dybas et al. 1989).

Dybas et al. (1989) determined the toxicities of EMA (MK-243), abamectin, two carbamates, and two SP's in tests with the larvae of three major lepidopteran cotton insect pests (Table 2). The LC_{50} values showed that EMA was significantly more toxic to the three lepidopteran species than the other pesticides. It is remarkable that against CBW, cypermethrin was less toxic than EMA by a factor of 0.005; that is, EMA was 205 times as toxic as cypermethrin. As a contact insecticide, however, EMA was only slightly more toxic than the SP's. Nevertheless, due to its unique mode of action, EMA should be extensively tested under field conditions and in various formulations for selectively controlling lepidopterous larvae in cotton.

Azadirachtin

Azadirachtin (AZ) is a tetranortriterpenoid (limonoid). Its structure was fully elucidated by Bilton et al. (1987) and is shown in Figure 5. AZ is the most important insect-active component of the seeds of the neem tree, or Indian lilac [*Azadirachta indica*], belonging to the Meliaceae (mahogany) family. There is a long history of folklore

medicine and insect control associated with the neem tree. The properties and potential of neem in insect management was recently reviewed by Schmutterer (1990).

AZ acts as an insect growth regulator apparently by blocking the action of the moulting hormone ecdysone. It also has a phagorepellent action in locusts and other insects. In addition to AZ, other neem seed kernel extracts (NSKE) and extracts of neem leaves have been shown to produce a variety of repellent, oviposition inhibition, feeding deterrent and morphogenetic effects in various insects. Presently, only the most active insecticidal ingredient, AZ, has been registered for nonfood use on ornamental crops. Under the tradename Margosan-O, AZ is used against the greenhouse whitefly [*Trialeurodes vaporariorum* (Westwood)], the sweetpotato whitefly, mealybugs, leafminers, and several lepidopterans at rates of 20 to 50 g AZ/ha. A strain of the sweetpotato whitefly has become a major pest of cotton in the western United States and appears to tolerate most insecticides. There is a possibility that it was introduced from the Middle East, where it is already the major pest of cotton.

Price and Schuster (1990) reported promising control of second-stage nymphs of the sweetpotato whitefly with single foliar spray applications of 220 ppm AZ Margosan-O to poinsettias. Promising control was also reported on tomatoes by Schmutterer (1990). These results suggest that AZ should be extensively tested for whitefly control on cotton.

Neem-based pesticides have proved to be relatively harmless to many beneficial insect parasites and predators and also to honey bees. The weak contact toxicity and selective mode of action are most likely significant contributors to this bioactivity profile (Schmutterer 1990). Neem-based pesticides also have a favorable acute toxicity profile in warm-blooded animals and fish, and a rapid disappearance rate in the environment.

Bacillus thuringiensis (B.t.)

Great hopes were generated in past years to control the "Heliothis" complex in cotton with spray formulations of spores of *Bacillus thuringiensis* Berliner var. *Kurstaki*. Field trials conducted over several seasons with strains HD-1 and HD-263 failed to provide economic control (Menn, King, and Coleman 1989). Although *B.t.* is a relatively

effective stomach poison, a residual contact toxicant is required to effectively control the "Heliothis" complex. *Heliothis* larvae feed sparingly on foliage and rapidly invade squares and bolls, thus escaping surface residues.

Renewed interest in *B.t.* has been generated recently spurred by advances in biotechnology. Through genetic engineering, the *B.t.* delta endotoxin gene has been successfully expressed in cotton plants, producing transgenic plants that are toxic to lepidopterous larvae feeding on cotton. Currently field trials are under way in Mississippi to evaluate protection of transgenic cotton plants from attack by first instar larvae of *Heliothis virescens*. These trials are being conducted cooperatively in the United States by the Monsanto Agricultural Company, St. Louis, Missouri, and the USDA, ARS, Crop Science Research Laboratory, Mississippi State, Mississippi (J.N. Jenkins, personal communication).

Biochemical Design

Most insecticides were discovered by the empirical or random synthesis-and-screen approach. However, as discussed earlier, more and more resources and attention are being directed toward biochemistry and physiology in designing novel pesticidal molecules. It was this cogent biorational approach that led to the design and synthesis of juvenoids that disrupt insect development (compounds mimicking the action of juvenile hormones) (Menn and Henrick 1981). Unfortunately, exposure to sunlight caused many of the juvenoids to become unstable and inactive against insects attacking cotton.

A recent breakthrough was the discovery of the first potent nonsteroidal agonist of ecdysone (Wing et al. 1988). This compound, RH-5849 [1,2-dibenzoyl-1-tert-butylhydrazine] (Figure 6), was discovered as a result of a long-term biorational program to discover antijuvenile or moulting hormone inhibitors at the Rohm and Haas research laboratories.

When injected into larvae of *Manduca sexta* (L.), RH-5849 was 50 times more active than 20-hydroxyecdysone in initiating premature moulting. It was even more effective in larval diets where it was 670 times more active than 20-hydroxyecdysone in initiating premature moulting. Similar

activity was determined in members of three other lepidopteran families; Noctuidae, Pyralidae, and Pieridae (J.A. Svoboda, personal communication, 1989).

Biochemical studies (Wing 1988) established that RH-5849 is a true ecdysone agonist and does not compete directly with ecdysone for target tissues. Although similar in chemical structure to the benzoylphenylureas that interfere with chitin biosynthesis, RH-5849 has a markedly different mode of action.

The novel and selective mode of action of RH-5849 which results in rapid cessation of feeding regardless of age or instar suggests that this compound, and possibly more active analogs, should be field tested in IPM programs for cotton. However, like the avermectins, this class of ecdysone agonists may suffer from the drawback that they are primarily active via ingestion. Experience has shown that the most successful insecticides against lepidopterous pests of cotton exert their primary action via contact.

Nevertheless, since seldom do such exquisitely selective compounds come along, every opportunity should be afforded to exploit their unique action through further synthesis of analogs and extensive field testing in cotton.

Semiochemicals

Semiochemicals, including pheromones, attractants, feeding stimulants and arrestants have been used in cotton and other crops for a number of years primarily for monitoring population densities of several pest species.

Only very recently has the technology of using semiochemicals to disrupt mating and to mass-trap insect pests become economically feasible for controlling two major North American pests of cotton--the boll weevil and the pink bollworm.

In the Mississippi Delta cotton region, a mass-trapping system has proven economically feasible for controlling boll weevils in the early season. McKibben and co-workers (McKibben et al. 1990) developed an attracticide trap. The ingredients consist of 40 μ g grandlure, feeding stimulants, cottonseed oil, and 1 g cyfluthrin formulated in polyvinyl chloride. (Grandlure, the boll weevil pheromone, is made of four unique alicyclic compounds--two alcohols and two aldehydes.) To this mixture are added a natural shellac, as

a binder, and a green pigment. This mixture is applied to wooden stakes placed vertically in the field at the rate of two stakes per ha. This trapping system attracts both sexes and has proved highly efficient in mass reduction of weevil populations. The traps need to be recharged every 4 weeks and are employed during a 2-month period. This selective population management system has the potential to become important for controlling boll weevils in the early season and may significantly reduce the need for large-scale treatments with insecticides.

In recent years, the cotton acreage in Arizona, the Imperial Valley of California, and the northeastern valleys of Mexico have drastically decreased or disappeared altogether because of the ravages of the pink bollworm. A new technology based on mating disruption that had its genesis in the pioneering research of Shorey and co-workers (Shorey et al. 1976) is now coming to practical realization. Large-scale field trials are currently under way in the Parker Valley of Arizona to evaluate the commercial potential of several formulations of gossypure to disrupt early-season mating and, thus, preclude the need for treating the cotton fields with insecticides early in the season (Brosten and Simmonds 1990).

Staten and co-workers (1987) obtained promising field results in the Imperial Valley of California and in the Mexicali Valley, Mexico, with hand-applied PBW-ROPE dispensers containing 78 mg of 96 % (Z,Z) and (Z,E) isomers of gossypure in a ratio of 49:51 respectively. Field laborers placed the dispensers around the stem of individual plants at the first-flower-bud stage and at a rate of 1000/ha. The gossypure remained active for approximately 60 days. Use of the dispensers reduced the need for insecticide applications by 41 % and resulted in a 97 % reduction in trap catches of the moths in August.

It is evident from the foregoing that semiochemical technology may have an economic future in IPM programs. It may help us improve the quality of the environment by enabling us to greatly lower our use of chemical pesticides.

The increased emphasis on IPM and environmental, economic and social pressures and demands are causing dynamic changes in the development of new chemicals for insect and mite control. The most obvious outcome is a drastically reduced number of new chemical compounds

appearing in the marketplace. Several of the new chemical insecticides and miticides presented here would seem to be compatible with biological control agents and semiochemicals in improved pest management systems for cotton. However, extensive field experience will be required to verify this.

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Table 1. Primary stages involved in discovery and development of a pesticide

Activity	Time Frame (Months)
Synthesis and initial bioscreen	18
Advanced bioevaluation	24
Development	40
Field trials	
Formulations	
Metabolism and environmental studies	
Toxicology (acute and chronic)	
Test marketing and sales	12
Total	96

Table 2. Toxicities of EMA and abamectin, two carbamates, and two synthetic pyrethroids when tested on neonate larvae of *Heliothis virescens* (TBW)¹, *H. zea* (CBW),¹ and *Spodoptera eridania* (SAW)¹

Compound	LC ₉₀ (ppm) at 96 h ²			Relative potency EMA
	SAW	TBW	CBW	CBW
EMA (MK-243)	0.005	0.003	0.002	1.0
Abamectin	5.83	0.128	0.21	0.01
Methomyl	8.6	10.0	8.1	0.00025
Thiodicarb	4.42	5.0	6.6	0.0003
Cypermethrin	---	---	0.41	0.005
Fenvalerate	1.34	1.5	---	---

¹ TBW - tobacco bud worm; CBW - cotton bollworm; SAW - southern armyworm.

² Bioassays based on exposure of larvae to treated foliage in enclosed containers.

Adapted from: Dybas et al. (1989).

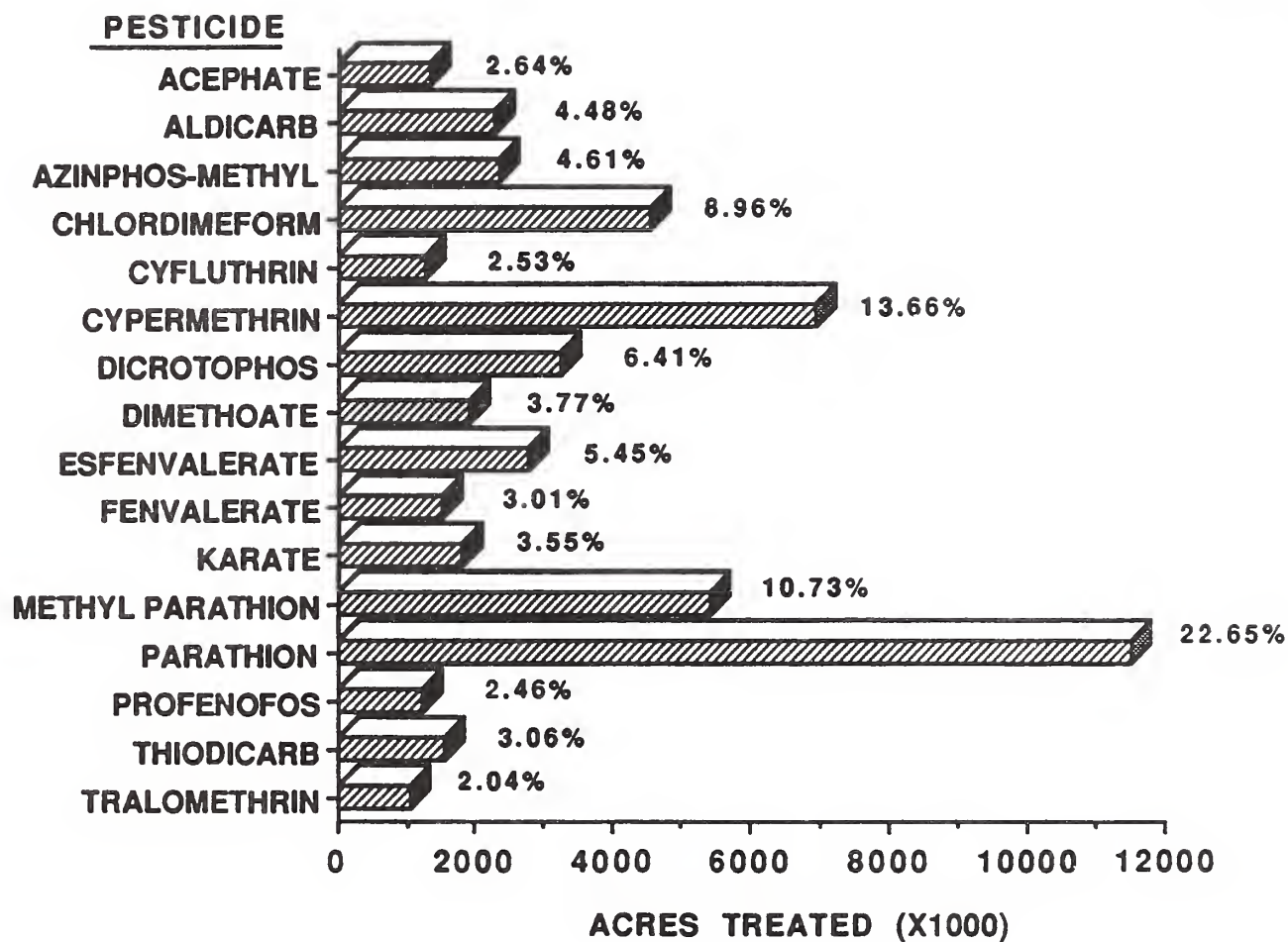
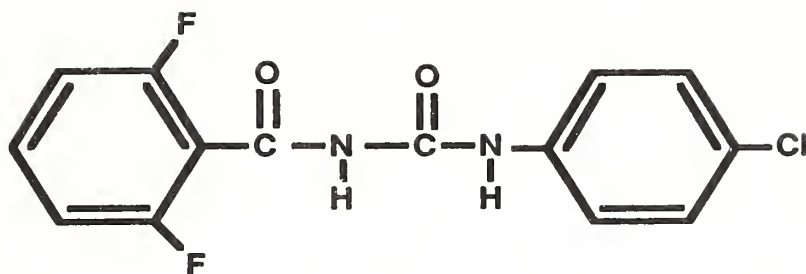
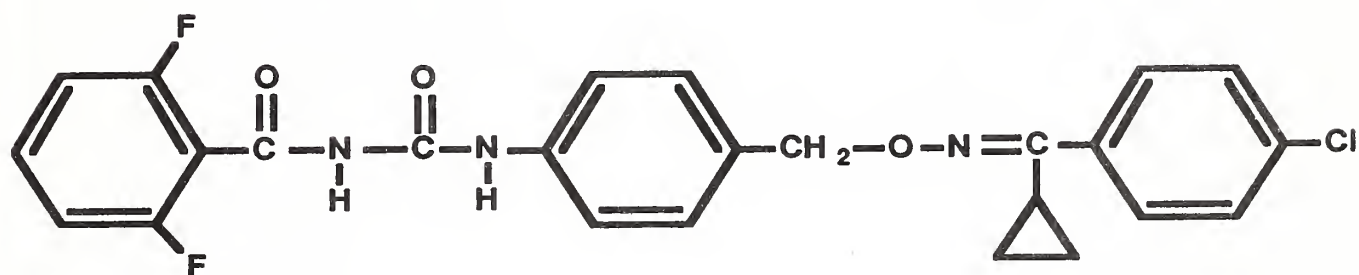


Fig. 1. Insecticide use on U.S. cotton, 1988.



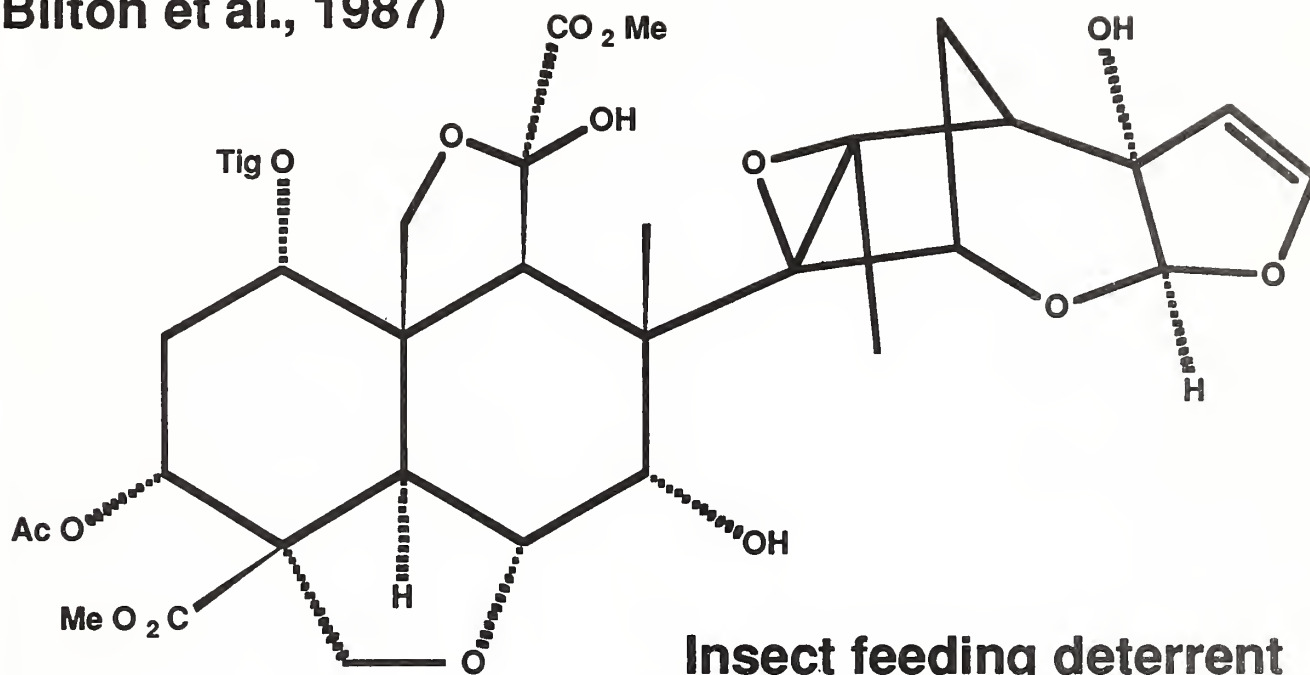
Diflubenzuron (PH 60-40)



Andalin (Duphar)

Fig. 2. Structures of benzoylphenylurea insecticides: diflubenzuron and andalin.

Azadirachtin (Bilton et al., 1987)



Insect feeding deterrent

Insect growth regulator

Fig. 5. Structure of the botanical insecticide azadirachtin (Bilton et al. 1987)

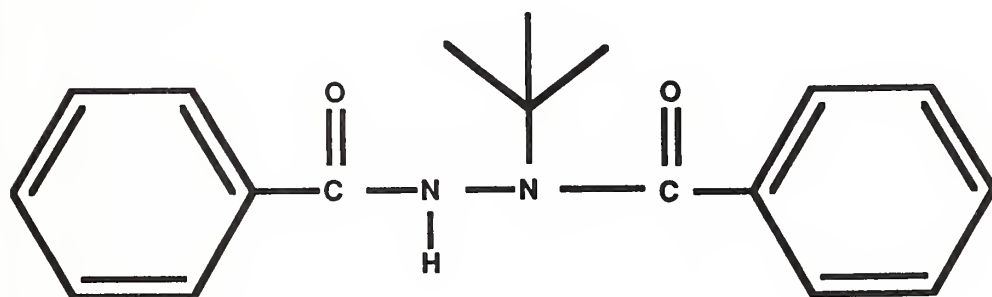


Fig. 6. Chemical structure of the ecdysone agonist, RH-5849 (Rohm & Haas)

Systems Analysis and Modeling for Decision Making in Pest Management

Terence L. Wagner¹

Abstract

Models describing agricultural systems have changed dramatically over the last two decades. They have changed in composition, form, and how they are applied. Early cotton models described the growth and development of an average plant. Models developed for integrated pest management described populations of plants and insects. From the outset, they were used as research tools, but recent advancements in computer science and artificial intelligence have made them viable management tools. As management aids, models have progressed from decision support (simply providing information on which decisions can be based) to actually making decision recommendations. Exciting innovations are on the horizon that will further expand the form and function of agricultural models.

Introduction

Imagine you are responsible for managing 500 hectares of cotton, and your livelihood depends on your success. The cotton is planted on fairly productive land within a farming community of mixed private ownership, part of a larger landscape containing an assortment of crops and woodlots. This situation is fairly common in the Cotton Belt of the United States.

Your job is to select the best cotton variety for the growing conditions, determine the pre-plant fertilizer requirements and the best planting date. You will have to decide if, when, how much, how to apply, and what type of post-emergent fertilizer, plant growth regulator, and irrigation is needed; if, when, and how to control the numerous arthropod, disease, and weed species affecting the crop; when and how to terminate the crop, and when to harvest. Along the way, you will need to schedule conflicting management activities and make sundry other decisions that affect the future outcome of the crop. Assuming you are interested in making a profit, you will have to decide if, when, and how much pre-harvest crop to sell (playing the futures market).

Now imagine the type of expertise you will need to successfully accomplish these tasks. You will certainly have to call on knowledge from agronomy, plant physiology, soil chemistry, soil physics, entomology, pathology, weeds science, accounting, and marketing, to name a few. Considerable attention will have to be given to the uncertainties associated with the weather, equipment, scouting information, personnel, the market place, etc. These uncertainties will directly affect your choice of decisions, altering the risks associated with the production and sale of the crop. In addition, the risks of borrowing large sums of money to initiate and maintain production, without the assurance of a profitable return, will be worrisome.

This imaginary job assignment serves to demonstrate the nature of farming. It probably arouses similar reactions in all of us. Farming is anything but trivial, especially in today's highly competitive world marketplace. Farm managers must deal with enormous complexities, uncertainties, and risks in making decisions that affect their lives and livelihoods, and the returns are often marginal at best. Very few professions have these disincentives and pressures.

With these facts in mind, a relevant question to ask is: how can science help farmers improve their understanding of the systems with which they must deal, thereby reducing the complexities, minimizing the uncertainties, and lowering the risks of their business? This paper describes some of the general research directed at these issues, especially as it relates to systems analysis and modeling in agricultural management. In the process, I hope to convey the usefulness and some of the history of these approaches, using cotton as an example.

Foundations of Systems Research

We live in an extraordinary time of technological development, a prominent example is the computer. Over the last three decades computers have advanced from large machines that process data relatively slowly to small machines with fast processing speeds. In the United States, computer costs have decreased exponentially during this period, resulting in their emergence from obscure (yet exceptional) research facilities to the commonplace of the desktop. Concurrent developments in software systems have transformed computers into powerful, "user-friendly" tools with hundreds of applications. The applications have virtually

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eliminated the need to understand these complex machines, and in the process, have facilitated remarkable changes in many aspects of American life. Agriculture is no exception (Holt 1985).

Systems Science and Modeling

Systems science is the study of systems. Watt (1966) defined a *system* as "a group of interacting and interdependent components forming a unified whole" [from Getz and Gutierrez (1982)]. Thus, a systems approach to problem solving attempts to identify and understand the cause and effect relationships between interacting components of a system. It follows that systems analysis uses a systems approach to problem solving. Specifically, *systems analysis* is the application of quantitative and qualitative techniques that enhance the understanding of the interactions between system components (Getz and Gutierrez 1982). It is a holistic approach that explains the behavior of the entire system based on an understanding and description of its interacting parts.

The relationship of *models* to systems analysis is clear -- models represent and describe the nature of objects and events. If the problem calls for a systems approach (i.e., its goal is to understand and describe the relationships between system components) then models are an appropriate strategy for solving the problem. In fact, analytical models are an eloquent way of addressing these problems because of their simplicity, precision, and ease of integrating and describing interactions among objects and events. In this paper I will examine some of the ways in which analytical models (quantitative and qualitative) have been applied to agricultural problems.

To summarize the discussion on systems analysis, it can be thought of as a process that encompasses problem definition, system description (including the identification of system boundaries, component parts, and interactions), inquiry into the cause and effect relationships between components, synthesis of resulting knowledge into a working model(s), and testing the behavior of the model for realism. During analysis, knowledge gaps will be identified leading to additional inquiry, synthesis, and testing; and so the process continues.

An Argument For a Systems Approach In Agriculture -- Implementing More Effective Management

A systems approach is relevant for dealing with agricultural problems. The biotic, edaphic, and climatic elements of agroecosystems are extremely complex. They are composed of numerous interacting and interdependent parts that are dynamic in time and space. Because of these dynamic properties, agroecosystems can produce unexpected results. Kenneth Watt (1970) argued this point regarding pest management. He provided examples of counterintuitive situations relating to chemical control, citing cases where pesticides promoted and prolonged outbreaks of the very insects they were meant to regulate. He also cited an example meaningful to biological control, where a smaller number of parasite and predator species exerted better control than a larger number of species (apparently due to competition among the larger number of interacting species).

The information used to describe the status of the cropping system and upon which decisions are based is often incomplete, inaccurate, or dated. This condition, combined with the characteristics described above, make it very difficult to evaluate and decipher the singular and composite behaviors of the system through time. Thus, understanding how the system will respond to changing environmental conditions and to imposed alternative management practices is not always clear, not even to the experts who are responsible for its management.

Given man's limited ability to comprehend agroecosystem events as they unfold, there is a great potential for managers to take action when no action is needed, not take action when it is needed, or take the wrong action in a given situation. These actions may be ineffective, wasting time and money, or worse -- they may produce the opposite effect desired. Models have the power to integrate, analyze, and interpret complex information on multiple interacting variables in a manner not possible by man's reasoning power alone, not even that of the experts. They can be used to predict future events, study system behavior, test alternative hypotheses, and deliver management advice at the time when it is needed -- as events unfold. Agroecosystem models have the capacity to provide counterintuitive results not anticipated by the experts.

The Changing Status of Systems Research in Agriculture

The body of techniques and theories associated with systems analysis and modeling has changed considerably over the last three decades. Some of these changes are relevant to a discussion on computer-based management systems in agriculture. They serve as an excellent means for describing the transformation of models in agriculture, and because of the extensive modeling efforts on cotton, this cropping system will be emphasized here. Two types of changes will be discussed: those involving the description of the system under study and those dealing with the methods or tools of analysis used in modeling this system. Because these changes did not occur independently, they will be considered together.

Agroecosystem Structure

Biological systems can be classified hierarchically. For example, five levels of organization might be considered in studying and modeling agricultural systems: the organism, population, community, ecosystem, or landscape. Each level is a system in its own right, somehow subject to or dependent upon the level(s) above it. The individual plants and insects in a particular field can each be considered a system at the organism level. Groups of interacting plants and insects of the same species are systems at the population level, and groups of populations are systems at the community level. Higher up the hierarchy, multiple interacting communities in association with their abiotic environment form an ecosystem, and multiple interacting ecosystems form a landscape.

Selecting the proper level of organization is important in modeling biological systems, and is part of the problem definition that must be addressed prior to initiating study. As pointed out by Getz and Gutierrez (1982), this process is not always easy, even though the structure of each system is fairly well defined. The proper level of system organization depends on the type of questions being asked; and in modeling agricultural systems, the questions (or objectives) have changed over the years as has the technology supporting these alternate perspectives. The system of interest to agricultural scientists has expanded toward higher levels of ecological organization and greater levels of system complexity.

The Past

Early cotton modelers were interested in describing the growth and development of a single, average plant (Duncan 1971, Baker et al. 1972, Stapleton et al. 1973, McKinion et al. 1975). In this case, the system under study was the organism, and the components of interest were plant organs and the factors controlling their growth and development. The primary objectives were to understand and describe the theoretical yield limits of cotton. A good example of this work is SIMCOT II, the first simulation model to realistically describe the fruiting curves of cotton. This model quickly evolved into GOSSYM which, interestingly, made its public debut at a Russian symposium in 1976 (Baker et al. 1976, 1983).

The use of systems science techniques to study insect pest management had its origins in the 1960s (Watt 1961, 1966), but not until the following decade was there a rapid expansion of systems applications to these problems (Ruesink 1976, Getz and Gutierrez 1982). Several important events made this possible, including advances in computer technology. Just as important, however, was the changing opinion regarding the environment and its safeguard.

The use of chemicals had become the principal choice of pest control in the United States beginning in the 1950s. Their application became so widespread and heavy that some investigators labeled their use addictive (see Getz and Gutierrez 1982). By the 1960s, the hazards of pesticides were being widely documented and publicized (Carson 1962, Rudd 1964, Smith 1970), prompting calls for improved procedures and standards for their use (Pimentel 1970). These events acted as a catalyst for change, and in 1972, the government sponsored several large research projects directed at developing alternative pest management strategies within an integrated pest management (IPM) framework. Several projects in forest and agricultural systems were funded between 1972 and 1985. For example, the "Huffaker" and ensuing "CIPM" Projects applied systems science methodology to pest problems in alfalfa, apple, citrus (Huffaker Project only), cotton, and soybeans (Frisbie and Adkisson 1986). These accelerated research and development projects used simulation models to synthesize and unify knowledge about the cropping systems.

In contrast to the agronomists who were interested in modeling the theoretical yield limits of crop production, the IPM investigators were interested in a much broader problem -- understanding the impact of arthropod pests on the crop and developing new strategies of control. This problem required a higher level of system organization, and resulted in the selection of the population as the primary unit of investigation. The "life system" became a standard approach for organizing and studying the important components of the system. Clark et al. (1967) defined this term as "the part of an ecosystem which determines the existence of a particular population -- composed of the subject species and its effective environment." The concept even influenced our views of pest management, defined by Rabb (1970) as "the reduction of pest problems by actions selected after the life system of the pests are understood and the ecologic as well as economic consequences of these actions have been predicted, as accurately as possible, to be in the best interest of mankind."

So successful were the IPM projects that literally hundreds of crop, pest, beneficial, and economic assessment models were developed in the 15 years from 1972. These simulation models contributed to the understanding of process-level biology, population dynamics, and insect/host interactions, the development and testing of new management practices, and the evaluation of the pest status of certain species.

Wagner et al. (1991) recently reviewed the primary IPM models associated with cotton in the USA. Most prominent among the pest population models are five describing *Anthonomus grandis grandis* Boheman (Fye and Bonham 1972, Jones et al. 1977, Wang et al. 1977, Curry et al. 1980, and Gutierrez et al. 1990a), three describing *Heliothis virescens* (F.) and *Helicoverpa zea* (Boddie) (Stinner et al. 1974, Brown et al. 1983, Hartstack and Witz 1983), one of *Lygus hesperus* (Knight) (Gutierrez et al. 1979), three of *Pectinophora gossypiella* (Saunders) (Gutierrez et al. 1977, Stone and Gutierrez 1986, and Hutchison 1991), and one of *Pseudatomoscelis seriatus* (Reuter) (Hartstack and Sterling 1986). Most of these models were linked to a cotton model (Gutierrez et al. 1975, 1984, 1990b; Curry et al. 1980; Jones et al. 1980; Hartstack and Witz 1983; Brown et al. 1983), and some were combined with models of other pest or beneficial species (Brown et al. 1983, Hartstack et al. 1990).

Notwithstanding these accomplishments, very few of the IPM models have been used on the farm for management purposes. There are several reasons for this lack of use, not the least of which were difficulties of novice users interpreting model output (see Coulson et al. 1990a, Wagner et al. 1991). TEXCIM, a simulation model containing multiple pest species of cotton (Hartstack et al. 1990), is somewhat of an exception. Unlike other IPM models, components of TEXCIM have been under development for almost two decades, leading to farm application in 1988. Model application is limited in range and function, however, serving few users in the state of Texas for decision support only (Sterling and Hartstack 1987, Sterling et al. 1990). In this role, the model assists in problem solving by furnishing simulation results to the decision maker. Other early efforts attempting to apply simulation models to problem solving led to the development of well-defined computer aids called decision support systems (Coulson and Saunders 1987). Because the IPM models were not adapted to decision making *per se*, the consensus was that they fell short of their original expectations.

The Present

During the 1980s, research arising from computer science and artificial intelligence (AI) provided new techniques for encoding, analyzing, and adapting quantitative and qualitative information. These applications have had a remarkable impact on agricultural modeling in the last 5 years, particularly in the decision making and problem-solving domains. Again, the new technology and techniques combined with inadequacies of the past helped promote this redirection in research, this time to modeling the management process explicitly.

A prominent example of the new technology is the *expert system* (ES). These computer programs are designed to solve complex, but narrowly defined, problems by mimicking human reasoning. They apply information assembled from a domain expert, encoding information (generally) as a set of rules residing in a knowledge base. For this reason, ES's are also called knowledge-based systems. Initially, ES's were written in specialized languages such as LISP and PROLOG on expensive and dedicated computers that optimized symbolic computation. Symbolic computation involves the processing of symbols and relationships rather than numbers and characters.

Early development costs of ES's prohibited the application of this technology to most problems domains (McKinion and Lemmon 1985); but as knowledge-systems software became available in the mid-1980s, the applications expanded to other areas including agriculture. This software (called ES shells) provided a set of methods that empowered personal computers and workstations in the development of ES's, dramatically reducing their costs. Presently, several cotton pest models use ES's. CIC-EM (Cotton Insect Consultant for Expert Management) is an excellent example of a classic rule-based ES (Bowden et al. 1990)

Because the knowledge base of an ES is a collection of heuristic knowledge (containing opinions, judgements, generalities, and facts), these systems can take advantage of qualitative information that simulation models cannot. This feature makes ES's more tractable in dealing with management problems. However, ES's do not have the mathematical, and typically, the predictive powers of simulation models. The individual weaknesses of the two modeling approaches were offset by their merger, which was an extremely important step in adapting computer-based systems to problems of agricultural management. Combined ES's and simulation models are often called *model-based reasoning systems* (MBRS) (Intellicorp, 1986).

In 1985, the expert system COMAX (COTton MAnagement eXpert) was linked to the cotton model GOSSYM (Lemmon 1986, McKinion et al. 1989). This was the first MBRS in agriculture. Initial versions of GOSSYM/COMAX optimized the timing and amount of irrigation water and nitrogen fertilizer needed to develop the crop. The model also provided information that could be used to determine the timing of crop termination through the use of chemical defoliant and boll openers. During the pilot test (1984-1988), GOSSYM/COMAX accurately predicted crop yields, and through its expert advice, routinely increased farmer profits. These successes promoted its widespread use across the US Cotton Belt, resulting in 1988 in the establishment of the first federally-funded technology transfer unit to support an agricultural model. This group, called the GOSSYM/COMAX Information Unit, trains system users (e.g., cotton producers, extension service personnel, consultants, etc.), transfers technical knowledge to user groups, resolves user problems, and refers difficult problems back to the research group for additional work.

In 1990, GOSSYM/COMAX assisted in the management of about 750,000 hectares of cotton on over 300 sites across the Cotton Belt.

As an ongoing federal project, GOSSYM/COMAX is under continual development. Recently, a mouse-driven windowing environment was added to the model providing a "user-friendly" interface. When COMAX was written, commercial ES shells were not available. The knowledge base and inference engine were written in LISP on a Symbolics Corporation computer. COMAX is now written in C using ART-IM (a shell from Inference Corporation). It is also being redesigned, employing a tool-kit (modular) structure with advisors for irrigation, fertilization, and crop termination. An advisor for a cotton growth regulator (PIX) will soon be incorporated, and a large pest management advisor is in the prototype stage. This latter advisor, called WHIMS (Holistic Insect Management System), presently consists of a comprehensive rule-base for 10 arthropod pests. The development of an affiliated simulation model is underway using an *object-oriented programming* (OOP) approach (Olson et al. 1990a, b, c).

OOP is a programming paradigm that has several advantages over the approach used in conventional computer languages (Thomas, 1989). For example, it formalizes the concept of an object as the unit of modularity. Objects consist of data and a set of methods (e.g., mathematical functions). The methods manipulate the data and describe the behavior of the object. The state of the object (its data) is sheltered in private memory that is only accessed when the method is implemented (through a specific message). In this manner, the data is hidden from all but its intended use, a feature known as encapsulation.

Another feature of OOP is polymorphism, which describes the condition where multiple objects use the same message. Because each object has a different method, one message directed to several objects invokes different responses. There is no problem with multiple objects responding to the same message because a method is part of the object and not a global entity. A third feature of OOP is inheritance, or the ability of an object to acquire all the data and methods of other objects, in addition to those of its own. This feature provides structure to a program (similar to our view of ecological hierarchies), thus making multi-level modeling possible.

These combined attributes of OOP promote the reuse and understandability of code. They foster code sharing and co-development, factors that are important in large projects, especially if members of the development team are co-located. OOP creates a plug-and-play environment (for objects), making it easy to prototype and test new ideas. These benefits speed software development and maintenance.

Two additional MBRS's on cotton also employ elements of OOP, but these systems are interesting for other reasons as well. COTFLEX (Stone and Toman 1989) and CALEX (Plant 1989a, b) have adopted several programming and analytical features that have relevance to other agricultural models. The application of rule-based ES's in agriculture has presented several challenges to researchers, one involving the scope of the problem itself. As discussed, agricultural decision making involves the application of dynamic knowledge from multiple, interacting disciplines and sources. To be reliable, however, the problem domain of an ES must be narrowly defined.

To overcome this problem, recent ES's have employed a *modular design*. For example, COTFLEX employs three advisors that describe agronomic practices for farm management, pest management, and farm policy (Stone and Toman 1989). Each advisor consists of sets of ES's that are rigidly defined. When integrated, the advisors allow the overall system to address the broad problems of total crop management. This system is presently being tested in Texas.

Another challenging problem arising from the application of ES's in agriculture is that of scheduling crop production and pest control activities. These activities may temporarily conflict with one another. For example, it is difficult or even impossible to cultivate, apply fertilizers, or scout for pests immediately after irrigating. Activities may also interact in more subtle ways. For instance, agronomic practices such as irrigation and fertilization may predispose the crop to pest problems.

To deal with these issues, CALEX applies the concept of a *blackboard* within an object-oriented framework (Plant 1989b). Within the program, multiple "experts" individually analyze the state of the crop relative to their own knowledge (e.g., pest infestation level, nutrient demand, etc.). Each expert determines an appropriate response for a given field situation, writing a schedule of recommended

actions and other relevant information on the blackboard. The expert iteratively examines the responses of the others, and revises its schedule to account for conflicts or multiple influences. CALEX then synthesizes the management recommendations of all the experts in a clear and concise manner.

The issue of *uncertainty* is an active area of research in agricultural modeling. Agricultural systems are inherently complex and dynamic, creating uncertainty that directly affects the confidence of decisions. Several methods have been developed to deal with uncertainty in ES inference (Spielgelhalter 1986). For example, CALEX (Plant 1989a) applies certainty factors (c) as antecedents to rules. Conclusions drawn from these rules are displayed as categories: most likely to occur ($c=1.0$), very likely ($0.75 < c < 1.0$), reasonably likely ($0.5 < c < 0.75$), and possible ($0.25 < c < 0.5$). Conclusions with $c < 0.25$ are not displayed. In this way, the system provides the user with knowledge of all reasonable conclusions.

Bayesian Belief Networks (BBN) (Pearl 1988) are another inferencing formalism that deal with uncertainty. This approach has been selected for use in WHIMS, the pest management component of GOSSYM/COMAX (Olson et al. 1990b, c). It consists of a network of nodes and connecting arrows. The nodes represent the propositions that are modeled, and the arrows represent the causal relationships between nodes. For example, if an arrow points from node A to B, then A causes (influences) B. BBN's use Bayesian probabilities to represent and update the belief about the nodes in the system. By changing the belief at one node, change is propagated in both directions along the causal chain. This method has an advantage over typical rule-based ES's, which cannot easily accomplish bi-directional reasoning. It is also an example of *causal modeling*, which is a new approach from AI research that promises to further expand the flexibility and power of ES's.

The Future

The last 2 decades have brought extraordinary changes in agricultural models, both in their structure and function. Initially, models described the biological system only. Their complexity increased over the years, moving through the ecological hierarchy from levels of the organism, population, and presently to describing ecosystem interac-

tions. Models are now beginning to consider the next level, the landscape, to account for the management of mixed cropping systems and the utilization of multiple ecosystems by arthropod pests.

The use of *geographical information systems* (GIS) will promote this trend. A GIS is a computerized mapping system for capturing, storing, retrieving, and analyzing spatial and descriptive data (Coulson et al. 1989, 1990b). When integrated with an ES, the GIS can interpret relationships within and among landscape data themes, select appropriate solutions for management, and guide in the use of the system. This powerful new tool has important implications to ecosystem and landscape management and planning, and it will certainly be incorporated in agricultural models in the future. In fact, a GIS is presently being investigated for use in WHIMS.

Agricultural models no longer describe just aspects of the biological system. Whereas yield prediction and pest population dynamics were once the dominant themes, models now consider management, economic, marketing, and farm policy issues as well.

New programming languages and software techniques are changing the development, maintenance, operation, and look-and-feel of software systems. Development and maintenance are becoming easier, and the type of information going into the models is becoming more generalized. These types of developments will continue, making systems far more powerful and flexible.

These trends will allow greater numbers of persons with various backgrounds to contribute to the modeling process. They are already creating an environment where scientists at different locations can realistically contribute to the development of a unified model. For example, efforts are presently underway to coordinate all cotton modeling work within the USDA, Agricultural Research Service.

The role of models in agriculture has also changed from mainly research tools, to decision support, and presently decision making. The next step will probably involve decision implementation. For example, models will not only decide when to irrigate but will send messages that turn water valves on and off.

Conclusion

There is a relationship between the complex and dynamic nature of the agroecosystem, the uncertainty associated with its management, and the risks of decision making. By nature, complexity and change foster conditions of uncertainty, and uncertainty imposes risks on decision making. Many of the factors that promote uncertainty in agriculture are beyond the farmer's control. For example, he can do little about the weather, the general state of the economy, resource supplies, government policy toward agricultural products, the cost of borrowing money, etc. He can, however, adopt innovations that reduce the uncertainties and risks of doing business. These innovations should alter the methods of management, production, or distribution to favorably affect costs and revenues. Computer models are rapidly becoming a viable means of accomplishing these objectives.

The use of models in agriculture will not eliminate uncertainty and risk; but they will provide increased understanding of the ecosystem, thereby reducing risks to a point where alternative management practices can be adopted. Like all new innovations, there are risks associated with initial use. Just as the expectation of profit provides the incentives to adopting new technology, those who are first to accept these risks will reap the greatest benefits.

I believe it is not the direct risks associated with the use of this technology that will dictate the acceptance of models in the near term. These risks are minimal, as there are always checks on model behavior. It is the changes that the models will bring in management and production that are resisted, perhaps even feared. The adoption of pest management models will require reformed attitudes and approaches to pest control and will affect, most dramatically, our present use of pesticides. There are entire industries built around this 50 year-old technology that superimpose well established protocols on agro-business, especially in cotton. Herein lies the immediate problem -- gaining acceptance (or at least cooperation) from those who will be most affected by the impending changes.

While farmers tend to be conservative and risk averse (for good reason), they are also realistic business people. They must be in this highly competitive environment. Ultimately, they will decide the value and role of agricultural models. Given the rapid and exciting changes occurring in this area, I believe that models will play a vital role in

agricultural management -- from testing new ideas on the farm, to recommending actions that prevent or resolve problems, and implementing decisions in the future.

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Boll Weevil Eradication in the Western United States and Northwestern Mexico, a Cooperative Program

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Introduction

Anthonomus grandis Boheman, the boll weevil, has been found only sporadically as an economic pest in Arizona before 1978, and was usually associated with stub cotton (Fye 1968). Stub cotton is cotton grown as a perennial crop which, in its second year after planting, is grown from plant stubs remaining after plant stalks are shredded in the fall. It is a practice avoided by the majority of growers and usually prevented by regulatory law within each state because it enhances the biotic potential of the boll weevil and the pink bollworm, *Pectinophora gossypiella* (Sanders). In 1978, cotton growers in central Arizona, where climatic conditions favor stub cotton, sought and obtained regulatory changes to allow this practice. The resultant change was immediately followed by detection of economic populations of boll weevil for the first time since the 1960s (Bergman 1983). As reported by Bergman, populations were detected in 1978 only in three fields. By 1981, populations were found in 25 locations. Within three years, population centers were found across Arizona in such diverse places as Parker, on the western border of Arizona, Laveen in central Arizona, and in the San Louis/Mexicali valley of northwest Mexico. The weevil populations were no longer restricted to stub cotton and were now obviously well adapted to our desert climate. Economic damage was extensive and increasing in Arizona and threatening those desert valleys of California previously unaffected. By the end of 1984, a cooperative program in California, Arizona, and northwest Mexico was organized for initiation in 1985. This program was to include the Colorado River Basin, with parts of the Gila River Basin as a buffer (Figure 1). In 1987, after viewing the success of this program, the Arizona cotton growers agreed (with major funding) to conduct an expanded Arizona-U.S. Department of Agriculture Program starting in 1988 for the remainder of Arizona. This program is now in its final stages. This report will cover the activity of these two related projects which demonstrate the feasibility of eradicating a recently established boll weevil population that has adapted to irrigated cotton in desert climates.

Program Operations

The boll weevil eradication program, as operated in the western U.S., has followed modifications (minimal) of eastern programs. It has three operational aspects: 1) a required host free period of at least 60 days, 2) extensive population monitoring using grandlure baited pheromone traps, 3) treatment of infested cotton with 16 oz./acre ultra low volume malathion initiated at a low threshold, based on pheromone traps. It is important to note that all three phases of this program are critical and form an integrated complete program. Though each aspect will be separated in our discussion of methods employed, this integration of technology should not be minimized. Although the complete eradication program was carried out in two phases, operations have occurred with minimal managerial discretion, the Colorado River Basin program operated as a full eradication project in 1985 and continued through 1988. Population monitoring continues in this area with no significant treatments or weevil detection. The central Arizona program started in 1988, and is expected to have accomplished its goal in 1991. In all cases, the program technology used was the same from 1985 through the present time.

Cultural control is implemented on a mandatory basis (by law). It is not a voluntary program. Growers are encouraged to exceed its limits in terms of providing longer host free periods where operationally feasible. A 60 day host free period is minimal and required. Statutory regulations specify that all cotton residue (stalks and other crop debris) will be shredded and tilled into the earth by a specific plow down date. No cotton stalks will be permitted to re-grow. No cotton may be planted until a date 60 days after the mandated plow down date from the preceding season. Growers who do not comply are penalized by monetary fines. In effect, a 60 day host free period as prescribed by the above restrictions produces a longer biological host free period. This is due to the fact that weevils must have fruiting forms to reproduce. Once cotton is picked, shredded and tilled, it is more than 60 days before any hostable squares are available. Boll weevil will feed on a square about 3/16 of an inch in diameter. Thus, the minimum biological host free period is approximately 105 days, depending on the specific growing conditions for that season.

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Although cotton fruiting forms may be visually examined for reproducing weevil populations, the principle program monitoring activity is dependent on pheromone traps baited with grandlure. This represents 99.9% of all populations monitoring activities within a program. In our programs, the boll weevil trap used has been described by Dickerson et al. (1981). This trap uses a controlled release formulation of grandlure designed to emit an average of 0.5 mg per day for 14 days. Grandlure is a very potent aggregation pheromone capable of attracting large numbers of weevils in the absence of fruiting cotton in heavy populations as well as detecting extremely low level populations where only a few weevils are present in a field. Improvements in traps and lure formulations allowing this low level of population detection are among the single most important components of this program (Brazzel, unpublished). In this program, all applications of insecticide are based on population monitoring by this trap, except on very rare occasions, where incipient infield reproducing populations are detected by examination of fruiting forms.

The insecticide of choice in the western program has been malathion sprayed in ultra low volume (ULV) formulations. This material at over 91% active ingredient is sprayed without dilution at 16 oz. per acre. It is usually sprayed with a fixed wing aircraft at 120 miles per hour with 40 lbs. of pressure and twelve 80002 tee jet flat fan nozzles directed perpendicular to the path of the aircraft. In addition to fixed wing aircraft, the program also used helicopter applications and mist-blower ground equipment to treat with this material. These two alternatives are used where fixed wing aircraft cannot reach the target with spray or operate without creating environmental problems. These treatments are initiated throughout the program based on specific guidelines. Although these guidelines have been altered slightly to cover local needs, the program throughout has principally treated when two or more weevils have been captured in the spring as cotton reaches early bud formation. Treatment is initiated only after hostable flower buds or squares are present. This threshold continues through June. In July control activities are only initiated after 5 weevils per week have been captured in a given field. As the season progresses the threshold is again raised to 10 per week. This is done in October during the time when treatments are designed to reduce numbers which can successfully reach overwintering quarters.

Results

The Colorado River Basin program has now been completed as an eradication operation. All program statistics are shown in Table 1. With the exception of 1990, this program covered a minimum area of 181,926 acres in 1986, to a maximum of 305,561 acres in 1988. Traps were maintained between 1 trap for each 6.78 acres in 1986, to 1 trap for 9.48 acres in 1989. In 1990, when all evidence of boll weevils was eliminated, trap ratios were reduced. This elimination of weevil populations may be noted by examining the number of total weevils captured. In 1985, during the first year of operation with 9.8 acres covered by a single trap, the program operated a total of 25,252 traps weekly during the entire growing season. These traps captured 302,758 weevils (derived by summarizing all trap data as provided by field crews). As of 1989, a comparable number of traps, 26,816, captured a total of 751 weevils. It is important to note that only 20 of these weevils were captured outside the Gila river area, which served as a buffer zone between the Colorado River Basin area and the generally infested central Arizona region. These weevils were captured only when weevils are known to be dispersing out of or into cotton and were not considered to be part of a reproducing population. This has been verified in part by the total lack of capture in 1990. The areas requiring treatment also were comparably reduced as would be expected, and the cumulative acres treated were highest in 1985 at 307,134. It should be noted that this is an average of less than 2 treatments for each program acre. Treatments within the program area varied from areas with no treatment to fields requiring extensive treatment. The latter was restricted to only those supported by the trap detection of weevils. In 1990, no insecticides were applied in the Colorado River Basin eradication zone for boll weevil. It is interesting to note that California and Mexico were without treatment as early as 1988 within the non-expanded eradication zone. Even in 1988, of the 3,029 weevils captured, only 35 were captured outside the buffer zone in Arizona.

The central Arizona or expanded program began in 1988. This program started when weevil populations were expanding drastically toward the eastern edge of Arizona and into neighboring New Mexico. Population densities also were escalating drastically. This extreme population pressure may be noted by examination of numbers of weevil captured in 1988, the first year of program operation. This data is in Table 2. This program is now in its

third year. It will not be completed, i.e. at 0 weevils detected, before 1991 or 1992. It is, however, well on its way, as is indicated by the major decline in total weevils captured in the entire program area. Although we have summarized data in this paper through August 1, 1990, our populations have declined drastically from the 2,724,593 weevils captured annually in 1988. As of August 1, 1990, our total capture level has been at 2,853. Even if fall captures double or triple, there will be more than a 99% reduction in total population.

Summary

The boll weevil in the western irrigated areas is eradicable and will be eradicated by 1992 at the latest. If eradication had not been the chosen route, growers would have been in a constant expensive control program. This management program, being heavily dependent on pesticides, would have been expensive to the environment and to the economics of each grower. Benefits could be expected to be as good as those achieved in the southeast (Carlson et al. 1989) where a 97% return per total dollar spent was expected each year after the program was completed.

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Table 1. Colorado River Basin Boll Weevil Eradication Program Statistics

Year	Acres including Buffer Zone	Average acres/trap	Cumulative acres treated	Total weevils captured
1985	233,357	9.18	307,134	302,758
1986	181,926	6.78	109,385	53,672
1987	224,043	8.01	52,578	27,245
1988	305,561	9.57	35,373	28,433
1989	211,727	9.48	3,029	751
1990	67,000 ¹	23.23 ²	0 ²	0 ²

(As of August 1)

¹ Buffer zone only

² Ratio in non-buffer zone (central eradication zone)

Table 2. Central Arizona Boll Weevil Eradication Program Statistics

Year	Acreage	Acres per trap	Cumulative acres treated	Total Weevils captured
1988	426,466	8.59	859,429	2,724,593
1989	444,540	6.70	545,645	586,961
1990 ¹	431,776	6.26	24,829	2,853

¹ All data summarized through August 1.

Use of Fungal Pathogens for Biological Control of Insect Pests in Alfalfa

Raymond I. Carruthers¹ and Kirsten Hura²

Abstract

The U.S. Department of Agriculture (USDA) has been involved in the development of biological control for over 100 years. Most of these efforts have employed predators or parasites of insect or weed pests and only recently has much emphasis been placed on the use of pathogens (bacteria, viruses, fungi, etc.) as biological control agents of insect pests. Entomopathogenic fungi are important natural control agents of many insects including several pests of alfalfa. Basic fungal pathogen biology, life cycles and environmental factors regulating disease development and spread are discussed from ecological and pest management perspectives. Several different approaches to biological control are discussed including: awareness and conservation of natural biological control, enhancement of biological control impacts through manipulations, augmentation of natural enemy numbers, and introduction of exotic natural enemies. Future interactions between IPM, biological control, insect pathology and biotechnology specialists are discussed.

Introduction

Biological control, the use of natural enemies to help regulate pest populations, has been an important component of many Integrated Pest Management (IPM) programs. In most cases, biological control involves the use of parasites, predators or pathogens which attack, injure or kill the target pest. To that end, the U.S. Department of Agriculture has been involved in the development and implementation of biological control programs for insect and weed pests since 1888 when C. V. Riley helped to introduce the vedalia beetle for biological control of cottony cushion scale in California (Coppel and Mertins 1977, King and Coulson 1988). Most of these efforts have focused on the collection and use of exotic parasites and predators for control of pests of forests and agriculture. Several classical examples of biological control successes have been documented by Huffaker (1971) and by Coppel and Mertins (1977). Although some early attempts were made to use insect pathogens as biological control agents,

much less emphasis has been placed on microbial control than on other areas of biological control. Recently, however, interest has increased in the use of insect pathogens (bacteria, fungi, viruses, etc.) as biological control agents.

Some pathogens are known to produce widespread epizootics in nature, often decimating their insect host populations, yet scientists have been relatively unsuccessful in producing insect disease outbreaks at will (Carruthers and Soper 1987). Most research efforts have focused on isolating and culturing highly pathogenic microbes with characteristics favoring long-term storage and application, as if they were chemical insecticides. Although this approach has been successful with some bacterial toxins, the use of living microbes as replacements for chemical insecticides has usually resulted in unpredictable and inadequate responses under field conditions (Fuxa 1987). One of the primary reasons for these failures is our lack of understanding of the natural dynamics of host/pathogen life systems. Diseases develop in complex ways based on biological and physical associations between the host, the pathogen and the environment. Understanding these associations in general and more specifically on a system-by-system basis should significantly aid our ability to manipulate insect pathogens for IPM purposes.

In this paper, we will discuss important aspects of insect disease development in hopes of increasing research interest and use of fungal pathogens as biological control agents. Topics of discussion include; basic fungal pathogen biology, disease epizootiology, and the use of fungal pathogens for biological control of insect pests. Emphasis will be placed on use of these biological control agents in IPM systems and several examples from alfalfa production will be discussed.

Fungal Pathogen Life Cycles and Biology

Fungal pathogens, in particular, are important natural biological control agents of many insects and other arthropods and frequently cause epizootics which may significantly reduce host populations (MacLeod 1963, Burges 1981, Carruthers and Soper 1987, McCoy et al. 1988). They are known to cause mycosis in many different taxa of arthropods and in almost every order of the Insecta (Bell 1974, Gillespie and Morehouse 1989). They are known from all life stages of insects (eggs, nymphs, larvae

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and adults) and are commonly found in aquatic, terrestrial and subterranean habitats (Ferron 1978).

Although fungal pathogens have much in common with viruses, bacteria and other insect-pathogenic microbes, they are unique in many ways (Ferron 1978). Perhaps the most significant difference lies in the mode of infection; whereas most entomopathogens infect their hosts through the gut following consumption, fungi typically infect their insect hosts by direct penetration of the cuticle (Roberts and Humber 1981). Although adhesive processes have not yet been intensively studied, spores of entomopathogens are thought to adhere to the insect cuticle through a combination of physical and chemical interactions (Fargues 1984).

Spore germination and thus infection, is highly dependent upon environmental moisture and is thought to require free water (Newman and Carner 1975, Roberts and Campbell 1977, Shimazu 1977, Kramer 1980), but this requirement may be met by moisture conditions of the microclimate in the absence of measurable precipitation (Hall and Dunn 1957, Tanada 1963, Ben-Zeev and Kenneth 1980, Kramer 1980, Mullens et al. 1987). Penetration of the cuticle is accomplished by a germination tube originating from the spore or by a specialized appressorium which attaches to the cuticle and gives rise to a narrow penetration peg (Zacharuk 1973, Roberts and Humber 1981, Boucias and Pendland 1982; Wraight et al. 1990). In either case, penetration is both a mechanical and an enzymatic process (Charnley 1984, St Leger et al. 1987, 1988b; McCoy et al. 1988).

Once the pathogen has passed through the insect cuticle, it begins its vegetative phase of development in the host's hemocoel. Different fungal pathogens may produce either filamentous mycelia, discrete yeast-like structures (hyphal bodies), protoplasts (cells without cell walls) or combinations of the structures within the hemocoel of the host (Tyrrell and MacLeod 1972, Roberts and Humber 1981, Latge et al. 1988). These vegetative stages rapidly colonize the insect's circulatory system and affect the host by emitting exoenzymes into the hemocoel that allow the pathogen to digest and assimilate nutrient material from the host. The length of the incubation period (time from infection to host death) varies among species, however disease development during the vegetative stage is typically temperature dependent (Hall 1981, Carruthers et al. 1985a, Carruthers and Soper 1987).

Pathogens may simply overcome their hosts by consumption of the available nutrients in the hemocoel (Roberts 1981) or by digestion of host tissues and organs (Brobyn and Wilding 1977). In cases where fungi overcome their hosts after a relatively short period of vegetative growth, toxins produced by the pathogen are presumed to be the cause of death (Roberts 1981). Compounds toxic to insects are produced by several entomopathogenic fungi both *in vitro* and *in vivo* (Roberts 1981). However, their role in pathogen-induced mortality in nature is not well understood.

Shortly after host death, the fungus re-penetrates the host cuticle from within and terminates in the formation of sporophores (usually conidiophores) that yield asexual spores (conidia) which function as dispersive and infective units. In many species of fungi, the production of conidia is highly dependent upon moisture (Wilding 1969, Millstein et al. 1983). Conidia are the infective propagules of secondary infection and are important in determining the rate of disease development and spread within a season. Environmental factors which control conidial production, survival and germination are critical to the rate of epizootic development (Carruthers and Soper 1987).

Entomopathogenic fungi survive adverse environmental conditions or the absence of their host by producing resting spores or other resistant structures, or as dormant mycelia in dried insect mummies (Kenneth et al. 1972, Wilding 1973). When dormancy requirements have been met and other environmental conditions are correct, resting spores germinate to produce germ conidia which then initiate mycoses in susceptible hosts.

Disease Epizootiology

Under natural field conditions, disease development and spread are governed by characteristics of both the host and pathogen populations and by the environment in which their interactions occur. In managed ecosystems this scheme is further complicated as human intervention adds a fourth component. These four components (host, pathogen, environment and human intervention) and their interactions have been represented by the disease tetrahedron (Zadoks and Schein 1979, Carruthers and Soper 1987). The factors encompassed by this model are necessarily interrelated and

although they may be discussed individually, it must be remembered that their interactions are critical to overall system behavior.

The Pathogen Population

Properties of the pathogen population which are important in epizootiology include virulence and pathogenicity, dispersal and survival in the host's environment, and inoculum density and spatial distribution (Tanada and Fuxa 1987). Most fungal pathogens are considered highly virulent relative to other pathogens because they have short incubation periods, produce copious amounts of secondary inoculum and can cause a rapid increase in disease prevalence. A fungal species that is pathogenic on a wide range of hosts may be more likely to persist in an environment because of the availability of alternate hosts. With a greater number of susceptible hosts there may be a greater reservoir of inoculum available to produce an epizootic (Tanada 1963). Pathogen survival in the host's environment is necessary for the long-term persistence of disease in the population; as previously mentioned, fungi accomplish this by producing various types of resting spores or structures. The ability to survive adverse conditions or periods of host absence may determine the frequency with which epizootics occur, because without some means of survival, infection is dependent upon the movement of inoculum into the host's habitat (Tanada 1963).

Dispersal is necessary for the rapid spread of disease. Abiotic factors such as rain or wind may carry spores, or the movement of infected and uninfected hosts may transport inoculum from one place to another (Hall and Dunn 1957). Some fungal pathogens cause their hosts to climb to aerial locations just prior to death (MacLeod 1963); such behavior may aid dispersal of infective conidia which may shower down upon or blow to nearby hosts. Pathogen population density and spatial distribution are key factors in the development of an epizootic because they affect the likelihood of contact with viable hosts (Tanada and Fuxa 1987). There has been substantial work on the relationship between pathogen density and mortality in the laboratory, generally concluding that mortality increases with increasing inoculum (Pinnock and Brand 1981). Although this relationship has rarely been studied under realistic conditions, field infection studies reveal that natural infection may follow a logistic response curve (Feng et al. 1990).

The Host Population

Important host population factors that must be considered are susceptibility, density, movement, and spatial distribution of individuals. Although host susceptibility may vary between geographic regions, there are very few reports of genetic variability in susceptibility of insects to fungal disease within local host populations. Paperiok and Wilding (1979) reported that one of two clones of the pea aphid (*Acyrtosiphon pisum*) from alfalfa was resistant to infection by *Conidiobolus obscurus* (Hall and Dunn) Remaudiere and Keller, compared to the other highly susceptible clone. Milner (1982, 1985) was able to characterize field-derived clones of pea aphids, also from alfalfa, as resistant or susceptible based on percent mortality when exposed to a particular isolate of *Pandora neoaphidis* (Remaudiere and Hennebart) Humber (= *Entomophthora aphidis*, *Erynia neoaphidis*). Undoubtedly the population dynamics of variability in host resistance and pathogen virulence would have an impact on epizootiology and the long-term stability of disease incidence in the population; however, this is an area of research which lacks sufficient study.

Host density may directly influence the rate of disease build-up by increasing host-to-host contact or by increasing the levels of secondary inoculum (Carruthers et al. 1985b, Benz 1987, Watanabe 1987). In some situations the spatial arrangement of hosts may be as important as the actual density of the host population. If hosts are highly aggregated it may be difficult for the pathogen to disperse between aggregates, unless infected hosts or pathogen propagules are highly mobile.

The Abiotic Environment

Abiotic environmental factors such as moisture, temperature, and solar radiation affect the rates of many biotic processes important for disease development; moreover, they may determine whether or not infection can occur at all. Atmospheric moisture is often considered the most important abiotic factor in the epizootiology of fungal diseases (Nordin et al. 1983, Fuxa and Tanada 1987). As mentioned in the previous section, germination and sporulation of most fungi are highly dependent upon moisture. However, fungi are able to acquire moisture in forms other than just precipitation, such as from dew set on plant surfaces or from the boundary layer of the host itself. The

humidity of the microclimate, such as that associated with a dense plant canopy, may be much higher than that of the ambient air, even under dry conditions (Tanada 1963, Kramer 1980, Fuxa and Tanada 1987).

Temperature-dependent processes which directly affect disease progress are the rate at which insects develop, the rate of fungal development within the insect, and the rate and quantity of spore production (Benz 1987). Most fungal pathogens, however, do well at all temperatures suitable for insect growth (Benz 1987). Fungal spores, particularly conidia, may be very sensitive to solar radiation and desiccation (Ignoffo et al. 1977, Carruthers et al. 1988). Spore longevity, germination potential and secondary infection levels may be increased if the microhabitats, such as a dense plant canopy, can protect the spores from harmful environmental conditions.

Interactions

Secondary infection is crucial in the epizootic development of fungal diseases, in that repetitive cycles of infection result in a rapid increase in disease prevalence (Zadoks and Schein 1979). Pathogens which have many secondary cycles during one or a few generations of the host are most likely to cause dramatic epizootics. This is particularly true if this process occurs in an environment that is conducive to pathogen survival and host infection. Transmission efficiency has been shown theoretically to be an important parameter related to the rate at which secondary infections occur and thus of epizootic progress (Anderson and May 1980). Transmission of fungal pathogens occurs primarily through the insect integument; this may be accomplished through direct host-to-host contact or by host contact with infective spores in the environment, such as conidia deposited on plant surfaces. Disease transmission is thus influenced by host and inoculum density and spatial distribution.

Theoretical models have demonstrated that a pathogen can only be maintained within a host population if host density exceeds a threshold value, and this value has been defined as inversely proportional to transmission efficiency (Anderson and May 1980). Brown and Nordin (1982) determined that the threshold density for *Zoophthora* sp. epizootics of alfalfa weevil populations is 1.7 weevils per stem. Subsequent field studies showed that larval densities below this threshold could not support a *Zoophthora* epizootic.

Nordin et al. (1983) concluded that the initiation of disease was best correlated with degree-day accumulations, and that epizootic dynamics were controlled by atmospheric moisture levels as long as the host population remained above the threshold density. Further methods of enhancing the development and spread of *Zoophthora* sp. are discussed in a subsequent section.

In recent years, systems analysis and modeling have been recognized as useful aids to understanding the complex dynamics of fungal epizootics (Anderson and May 1980, Carruthers 1985, Brown 1987, Carruthers and Soper 1987, Carruthers et al. 1988, Onstad and Carruthers 1990). Relatively simple models have been used to explore basic questions in epizootiology (Anderson and May 1980, Anderson 1982, Brown and Nordin 1982, Brown 1984, Regniere 1984, Hochberg 1989). More detailed simulation models of specific host/pathogen systems have also been developed for a few fungal pathogens (Carruthers et al. 1986, Carruthers et al. 1988). These models and the techniques of systems science have proven to be very useful in guiding the collection, analysis and synthesis of information about the dynamics of host and pathogen life systems. In addition to providing basic understanding, models can assist in pest management decision making and can be used to help design and evaluate strategies for employing fungal pathogens in biological control programs. Expert systems (Logan 1988) and intelligent modeling systems (Larkin et al. 1988, Larkin and Carruthers 1990) are becoming available to make the analytical power of systems techniques more accessible to scientists and pest management specialists who may have little experience with modeling.

Although epizootics of fungal disease are known to cause major declines in pest populations, very little information is available on the long-term regulatory ability of these pathogens. This is particularly true during periods of enzootic activity when disease prevalence is low and signs of host infection are difficult to detect. Disease assessment is complicated further if pathogen-induced mortality occurs in habitats difficult to observe, as is the case in soil or aquatic ecosystems. Over the past two decades, however, several significant descriptive and experimental studies on disease dynamics have provided new insights into the population biology and possible use of fungi as biological control agents (MacLeod et al. 1966, Soper et al. 1976, Kish and Allen 1978, Soper and MacLeod 1981, Nordin et

al. 1983, Carruthers et al. 1985b). Their effects in regulating insect pests of alfalfa are particularly noteworthy and will be discussed in detail below.

Biological Control of Alfalfa Pests Using Fungi

Naturally occurring epizootics caused by fungal pathogens, particularly those caused by fungi in the Order Entomophthorales, are frequently noted in both natural and managed ecosystems (including alfalfa) (Pickford and Riegert 1964, Wilding 1975, Soper et al. 1976, Mohamed et al. 1977, Wilding 1981, Nordin et al. 1983, Carruthers et al. 1985b, Lewis and Cossentine 1986, Carruthers and Soper 1987, McCoy et al. 1988). Due to the catastrophic impacts these pathogens have on their host populations, they hold significant potential for biological control of many pest species (Ferron 1978, McCoy 1981, Wilding 1981, Carruthers and Soper 1987).

The use of entomopathogenic fungi for biological control in managed ecosystems has followed four basic strategies; 1) Awareness and conservation of natural biological control, 2) Enhancement of biological control through active manipulations, 3) Augmentation of natural enemies, and 4) Introduction of exotic natural enemies (Ignoffo 1985, McCoy et al. 1988). We will provide examples of research that demonstrates current levels of expertise and important aspects of these areas of biological control of insect pests on alfalfa.

Alfalfa, *Medicago sativa*, is the world's most valuable forage crop, providing the best food value for all classes of livestock. Forages provide in excess of half the feed units for livestock, which in turn provides half of the nutrients used by American consumers. In addition to its nutritional value, alfalfa is important since it has high nitrogen fixing capabilities and because it is a soil-conserving perennial crop. Alfalfa is grown on over 26 million acres in the United States and is exceeded in U.S. production acreage only by corn, soybeans and wheat. Alfalfa, however, exceeds each of these crops in protein output per unit area, producing an overall U.S. cash value estimated in excess of \$6 billion per year (USDA 1989). Alfalfa provides food and shelter for a diverse group of insects, several of which are major economic pests. Although the pest complex varies regionally, six major groups (weevils, plant bugs, aphids, grasshoppers, leafhoppers and leafminers) cause damage to

alfalfa across the United States. Although other insects can periodically become pests, the main pest species in the northeastern and north central United States are the alfalfa weevil (*Hypera postica*), spotted alfalfa and pea aphids (*Therioaphis maculata* and *Acyrtosiphon pisum*, respectively), the alfalfa blotch leafminer (*Agromyza frontella*) and the potato leafhopper (*Empoasca fabae*). Biological control has been researched and/or implemented for most of these pests, and control has been successful in several cases (for parasitoid and predator examples see article by G. Cunningham, USDA-APHIS). The alfalfa weevil, alfalfa blotch leafminer and most aphid species are currently under biological control throughout most of the northeastern and north central United States.

Of the five major pests of alfalfa listed in the previous paragraph, four are known to have fungal pathogens that exert high levels of mortality under some field situations. Some of these pathogens were found to occur naturally while others were introduced as exotic biological control agents.

Although several host/pathogen associations from the alfalfa production system could be discussed, the following host and pathogens were selected as they provided examples of the four general strategies of biological control now used for fungi. These examples also illustrate the potential impacts of fungal diseases on four of the most important alfalfa pests of the northeastern and north central United States. While some of these pathogens being discussed are currently operating as fully-functional biological control agents, others are still in the research and developmental stages. We hope to provide an up-to-date status report on each of the pathogens discussed, although limited space required exclusion of many specific details.

Awareness and Conservation of Naturally Occurring Pathogens

As previously mentioned, dramatic epizootics which cause high rates of mortality have been reported from many different cropping situations, including several examples from alfalfa (Arthor 1886ab, Hall and Dunn 1957, Harcourt et al. 1974, Harper 1987). Rapid disease spread and high rates of mortality frequently attract attention and generate interest in fungal pathogens for use in pest control programs. The more typical situation, however, is an enzootic level of disease that often escapes our notice yet

causes significant pest mortality. The endemic occurrence of a pathogen at low-moderate levels may play an extremely important role in maintaining pest levels below economic thresholds. It is thus important to study and to evaluate the relative impact of all natural mortality factors (including fungi) on the population dynamics and regulation of any particular pest.

Recognition of natural pathogen-induced mortality, of any magnitude, is the first step to understanding and controlling the biotic and abiotic factors which influence infection rates. This understanding may allow producers to avoid pest related concerns or unneeded pesticide applications in some circumstances. Gaining insight into the operation of a naturally occurring disease is also the first step toward manipulating biological control agents for pest management purposes. Occasionally, insignificant changes in cultural practices may allow us to take advantage of natural sources of pest control that might otherwise be unavailable (see Brown and Nordin 1986, Carruthers et al. 1986, Carruthers and Soper 1987, Harper 1987). The first insect/ pathogen life system from alfalfa that we will discuss provides such an example.

The pea aphid, *Acyrtosiphon pisum* (Harris), is a cosmopolitan pest of many legumes which at high densities causes yellowing and stunting of alfalfa. In most areas of the United States pea aphid densities do not usually reach economic threshold levels. This natural control is presumably the result of mortality caused by introduced parasites and predators (Anonymous 1979, Edwards et al. 1979). The pea aphid has been found to be highly susceptible to several species of fungal pathogens which may cause dramatic epizootics, yet fungal pathogens have not often been considered as important biological control agents in alfalfa pest management programs.

Pandora neoaphidis (= *Entomophthora aphidis*, *Erynia neoaphidis* Remaudiere and Hennebert) Humber is the most common pathogen of pea aphids in the northern United States (Hutchinson and Hogg 1985, Hural unpublished data), Australia (Cameron and Milner 1981), and Europe (Wilding 1975). *Pandora neoaphidis* is apparently obligately asexual; no sexual or resting structures have been found in nature (Milner et al. 1980, Hural unpublished data). *Pandora neoaphidis* has a wide host range among aphids and has caused devastating epizootics in populations of *Myzus persicae*, *Aphis fabae*, *Capitophorus horni* (Missonier et al. 1970) and others (Milner et al. 1980).

Warm, wet conditions are generally necessary to cause epizootics (Rockwood 1950, Missonier et al. 1970, Milner et al. 1980, Milner and Bourne 1983).

Pandora neoaphidis infections begin to appear in early spring, soon after the aphids have emerged. Infections occur throughout the growing season and are greatly influenced by environmental conditions, particularly atmospheric humidity (Wilding 1975). Saturated conditions are required for conidial germination (Yendol 1968) and sporulation. It is unknown how this fungus overwinters, as resting structures have not been found. It has been suggested that it survives vegetatively in aphid cadavers (Wilding 1973, Courtois and Latteur 1984). Latteur (1977) suggested that conidia might be capable of surviving in damp soil but his data was not conclusive. Conidia do not survive long in air that is not saturated (Brobyn et al. 1985, 1987).

Recent field studies in Wisconsin and New York (Hutchinson and Hogg 1985; Hural, unpublished data) showed that *P. neoaphidis* infection is one of the most important mortality factors in pea aphid populations in alfalfa, typically outweighing parasites and predators. In the Wisconsin study, the mean number of embryos per adult decreased with the infection rate, which Hutchinson and Hogg (1985) assumed would result in a proportional reduction in birth rates. Time-specific life tables constructed for these populations indicated that the impact of *P. neoaphidis* on pea aphid density was mostly due to this reduction in adult fecundity.

In New York, the prevalence of *P. neoaphidis* infection is highest during spring and fall, and decreases during the warmest period of mid-summer. Because high temperatures also inhibit aphid development, pea aphid densities exhibit a similar pattern. *Pandora neoaphidis* infection is usually present throughout the entire growing season but only causes epizootics in the fall. The relative importance of *P. neoaphidis* and other sources of natural mortality such as parasitism by *Aphidius* and *Praon* species appeared to change throughout the season but more research is needed to determine exactly how these mortality factors interact in the field. It may, however, be possible to enhance or manipulate infection in this system by altering cultural practices or by providing inoculum earlier in the alfalfa production season.

Enhancement of Naturally Occurring Fungal Pathogens

Depending on specific details of the host and pathogen population and the associated ecosystem, enhancement of disease development and spread has been accomplished by a number of different methods (Hostetter and Ignoffo 1978, McCoy et al. 1988). Some specific methods include habitat manipulation, altering cultural practices such as planting or harvesting (Brown and Nordin 1986), and managing controlled inputs such as irrigation or pesticides (McCoy et al. 1976, Kish and Allen 1978, Sprengel et al. 1979; Hamm and Hare 1982). The following discussion of *Zoophthora* sp. mycosis of the alfalfa weevil is an example of how early harvesting has been used to enhance the effects of naturally occurring populations of this pathogen in an IPM program.

Zoophthora sp. mycosis of the alfalfa weevil: The fungal pathogen *Zoophthora phytonomi* (Arthur) Batko is known for its natural regulatory effects on populations of the clover leaf weevil, *Hypera punctata* in North America (Arthur 1886a,b; USDA 1956) and a related weevil species, *H. variabilis*, in Israel (Ben-Zeev and Kenneth 1980). Following the introduction of the alfalfa weevil (*H. postica*) into North America, 17 years of extensive surveys revealed no infections in *H. postica* populations (Puttler et al. 1978) until 1973, when a pathogen similar to *Zoophthora phytonomi* was first observed causing significant epizootics in alfalfa weevil populations throughout southern Ontario, Canada (Harcourt et al. 1974). Harcourt et al. (1984) suggest that this pathogen was one of the primary reasons for the major alfalfa weevil decline seen in Ontario during the mid 1970's. Subsequently, this pathogen spread into other North American alfalfa production areas where it also caused significant mortality of *H. postica* (Puttler et al. 1978, Gardner 1982, Nordin et al. 1983, Pienkowski and Mehring 1983). Taxonomic questions associated with this pathogen still exist, some evidence suggests that the pathogen that infects alfalfa weevils is a different species of *Zoophthora* than is found infecting the clover leaf weevil (Harcourt et al. 1981), while more recent finding suggest that the pathogen is actually the same pathogen (*Z. phytonomi*) that is found infecting the clover leaf weevil (R. A. Humber, unpublished data).

Due to uncertainty associated with the origin of this pathogen, it is unclear whether the pathogen causing mycosis in the alfalfa weevil was introduced into North

America in conjunction with weevil introductions or exotic parasite releases, or if the pathogen switched from another North American host species, possibly *H. punctata*, onto *H. postica*. Although the origin of this pathogen is still unknown (Puttler et al. 1978), the fungus has become well established as a major natural biological control agent of the alfalfa weevil throughout much of its range. Epizootiological studies have shown that disease prevalence varies between sites and seasons, but disease levels from 30-70% are not uncommon at the time of peak larval occurrence (Puttler et al. 1980), and have approached 100% late in the host's developmental cycle, particularly when densities are high (Harcourt et al. 1974, Nordin et al. 1983). Disease levels of this magnitude produce larval mortality between 65-90% with an additional 40-50% expressed in the less-visible pupal stage (Harcourt et al. 1974).

Brown and Nordin (1982) determined that a threshold host density (1.7 weevils/ alfalfa stem) was required for *Zoophthora* sp. to induce epizootics. Although this threshold varied with environmental moisture, low host densities were thought to limit early-season spread of mycosis. Using laboratory, field and simulation modeling experiments, Brown and Nordin (1986) developed early harvesting strategies that maximized the development and spread of *Zoophthora* sp. even when weevil populations were lower than critical levels for epizootic development. This was accomplished by harvesting the alfalfa when *Zoophthora* sp. mycosis of weevil larvae was first observed. Early harvesting is thought to increase disease prevalence because it: 1) concentrates larvae in windrows; 2) damages or stresses larvae making them more susceptible; and 3) alters micro-environmental conditions (increases moisture) to enhance sporulation, germination and thus infection. Research fields managed using this technique showed higher disease prevalence, which demonstrates that enhancement of fungal diseases is not only possible but is practical and economical as it is based on accepted production practices and equipment (Brown and Nordin 1986). However, a better understanding of the spatial distribution and dynamics of this pathogen is necessary to effectively implement this strategy in a statewide IPM program (Brown and Nordin 1986).

Augmentation of Fungal Pathogens for Biological Control

Augmentation (increasing pathogen inoculum density) through the development of microbial insecticides has received substantial attention and will only briefly be discussed here as it is the focus of several other articles (Burgess and Hussey 1971, Burgess 1981, McCoy 1990). It must be said, however, that augmentation has not only taken the form of microbials applied like pesticides with the goal of high acute host mortality, but has also been used to initiate epizootics prematurely (Ignoffo et al. 1976, Ferron 1981) or in situations where epizootics would not naturally develop (McCoy 1981, Riba 1984). In these cases, disease development is dependent not only on the efficacy of the fungal material originally applied to the target host but also on the pathogen's ability to become established in the environment and produce secondary inoculum capable of polycyclic infection. These methods of pathogen augmentation require detailed information about host, pathogen and disease dynamics which have only recently been researched (Allen et al. 1978, Carruthers and Soper 1987, McCoy et al. 1988).

Use of *Zoophthora radicans* (Brefeld) Batko for control of *Empoasca fabae*: Although several insect species attack alfalfa throughout the United States, the potato leafhopper, *Empoasca fabae*, is currently considered to be the most serious economic threat to alfalfa production (Gyrisco et al. 1978). Feeding by the potato leafhopper causes severe yellowing and stunting both in seedling and established alfalfa stands. Losses combined with control expenditures cost US alfalfa producers millions of dollars annually. Entomologists in Illinois and Wisconsin estimate that in the average season, yields are decreased approximately 20% in terms of quantity with additional losses of approximately 20% through reduced protein content. In addition, *E. fabae* is a major pest and virus vector in numerous crops (potatoes, soy and other beans, clovers and 100+ other cultivated plants), causing significant losses (Gyrisco et al. 1978).

Successful biological control agents, both insect parasitoids and microbial pathogens, are currently helping to reduce populations of other major alfalfa pests (e.g., the alfalfa weevil, the pea aphid and the alfalfa blotch leafminer) well below economic thresholds in many areas of the country (Dunbar and Hower 1976, Brown and Nordin 1982, Hower and Davis 1984). No such biological control organisms are

being used to manage potato leafhoppers. After five years of effort, the ARS-European Parasite Laboratory has terminated its program aimed at locating beneficial insects to control the potato leafhopper. Currently the only control option for leafhopper management is the application of chemical insecticides, which is not only costly but interferes with other highly successful biological control programs in alfalfa. More insecticides are now being applied to alfalfa in the central and eastern US to control *E. fabae* than all other insect pests combined. Microbial control of *E. fabae* may provide an alternate management tool in the alfalfa production system that would be more compatible with existing alfalfa pest management programs, provide less hazard to livestock and in general, would be more environmentally sound.

Initial research on the effects of *Zoophthora radicans* on *Empoasca fabae* was conducted through cooperative efforts of various agencies including USDA-Agricultural Research Service, USDA-Cooperative States Research Service and US-Agency for International Development. The USDA-ARS, Plant Protection Research Unit joined in an effort with the Boyce Thompson Institute for Plant Research, the Illinois Natural History Survey and Cornell University to explore the possibility of microbial control of the potato leafhopper using *Z. radicans* isolates collected from a related leafhopper species in Brazil. Through efforts made in this program, it became clear that *Z. radicans* had significant potential for biological control of *E. fabae* (Wright et al. 1985, 1986; McGuire et al. 1987a,b; Galaini-Wright et al. 1990).

Epizootic levels of *Z. radicans* are commonly seen in Brazilian leafhopper populations and are known to cause significant population reductions in both bean and cowpea crops (Wright et al. 1985, Galaini-Wright et al. 1990). Pathogen isolates from these epizootics were imported to the US and tested against the potato leafhopper under laboratory conditions at the Boyce Thompson Institute. These studies show that pathogen levels as low as 3.3 spores/mm² cause significant levels of infection (>70%) in late-instar nymphs. A ten-fold increase in dose (33.0 spores/mm²) repeatedly caused 100% mortality. Time from infection to host death and conidial production (pathogen multiplication) is very rapid, 2-4 days depending on host age and environmental conditions.

Zoophthora radicans is a very attractive pathogen for use in biological control since it may either be introduced in an

inoculative release or used more as a microbial pesticide through inundative releases (here we will discuss this second aspect). This pathogen can be easily produced in large quantities and stored for relatively long periods using the marcescence technology developed by the ARS-Plant Protection Research Unit (Soper and McCabe US-patent 4,530,834). Fungal mycelium can be grown in liquid media, dried, milled, stored and then applied in the field where it will rehydrate and produce infective conidia in patterns very similar to fungi growing directly from a newly killed host.

This material has been applied to small field plots and evaluated for its sporulation potential and pathogenicity to caged populations of *E. fabae*. These studies not only showed primary infection levels as high as 70% in caged leafhoppers within 24 hours, but also high infection levels in natural populations through mycosis of leafhoppers outside the test cages (Wraight et al. 1986). Inoculation densities of approximately 5.0 g/m² of dried hyphae were applied to a total of 12 m², inducing infection levels as high as 92% across a 0.75 acre test field over a three week sample period. The epizootic reduced leafhopper populations from 1.7 to 0.08 leafhoppers per stem. A second study conducted in an adjacent field gave similar results.

In Illinois, a similar release (using infected cadavers in a potato field) produced the same general results (McGuire et al. 1987b). Although not clearly documented in the year of release, *Z. radicans* became established in central Illinois and has caused substantial epizootics in leafhopper populations over the last few seasons. Infection levels as high as 90% have been recorded among leafhoppers in beans where the epizootics have been most evident. Since its introduction into Illinois, *Z. radicans* has spread approximately 20 miles from the original release sites and has caused major leafhopper declines in bean, potato and alfalfa crops. Additional introductions in Illinois and New York have continued to cause similar epizootics (Carruthers unpublished data).

Although a single isolate of *Z. radicans* has shown significant potential to control *E. fabae* under natural field conditions, several additional isolates have been collected from South America and Europe. A number of these isolates have shown equal or higher virulence to *E. fabae* in laboratory screenings than the material originally tested and released in the field. These isolates may also possess other beneficial characteristics, such as a faster speed of kill or

better overwintering ability, but are yet to be evaluated. Screening of this germplasm in the laboratory is currently underway and further evaluation of selected pathogen isolates will be conducted in the field following USDA-Animal, Plant Health Inspection Service and US Environmental Protection Agency approvals (summer 1990). Hopefully, these studies will allow us to use *Z. radicans* either as a myco-insecticide or as an introduced biological control agent throughout the full geographic range of the potato leafhopper (Carruthers and Soper 1987).

Introduction of Exotic Fungal Pathogens

Classical biological control (the introduction of exotic fungi, either new species or more virulent strains of a species that already exists) has received very little attention in the field of insect pathology (Roberts 1978). Some reports of attempts to establish exotic fungi include the use of *Coelomomyces stegomyiae* Keilin for mosquito control (Laird 1967), *Entomophaga aulicae* (Reichardt in Bail) Humber for control of the browntail moth (Speare and Colley 1912), *Entomophthora erupta* for control of the green apple bug (Dustan 1923) and *Zoophthora radicans* for control of the spotted alfalfa aphid (Hall and Dunn 1957, Milner et al. 1982). Although releases were made in each of these cases, detailed population assessments documenting the effects of these fungi were rarely conducted. The introduction of *Zoophthora radicans* into Australia provides an excellent example of an introduction of a fungal pathogen and its impact on the host population.

Introduction of *Zoophthora radicans* to control the spotted alfalfa aphid: In 1979, different isolates of *Z. radicans* were introduced into New South Wales (NSW), Australia in a cooperative effort between the USDA-ARS Plant Protection Research Unit and CSIRO for biological control of the spotted alfalfa aphid (Milner and Soper 1981). *Zoophthora radicans* quickly became established in NSW, caused epizootics in the pest population and spread over 200 miles from the original release site. In the third field season, *Z. radicans* was again found to induce epizootics (up to 74% prevalence) in sampled spotted alfalfa aphid populations (Milner and Lutton 1986) and has spread over 300 km from the original release sites (Milner and Soper 1981, Milner et al. 1980, 1982; Milner and Lutton 1983, Milner personal communication). This example demonstrates the potential for an exotic fungal pathogen to be successfully introduced, become established and provide ongoing regulation of an

insect pest of alfalfa. Further exploration and collection of fungal isolates from other important pest species could reveal additional untapped pathogens with potential for insect pest management.

Summary of Insect/Fungal Biological Control in Alfalfa

The four examples discussed above, demonstrate how fungal pathogens may be used in a number of ways to help manage insect numbers in alfalfa. Alfalfa is a particularly good candidate crop for a multifaceted biological control program using fungal pathogens. It is a low-value crop (compared to fresh market fruit and vegetables) so producers seek to minimize cash inputs for its management; the crop is primarily consumed by livestock, thus substantial cosmetic damage may be tolerated; and the structure of the crop canopy provided a moist and protected environment where disease transmission readily occurs. With additional research, pesticide application in alfalfa production may be further reduced while increasing the level of insect control.

Conclusions: Research Needs and Future Application of Biotechnology

Entomopathogenic fungi are important natural regulators of many arthropod populations, including several pest species. A variety of strategies have been used successfully to manipulate fungi in biological control programs. While there have been fewer documented biological control successes with fungal pathogens than with parasitoids and predators, much less effort and capital have been expended to understand and manage them. Most of the research conducted on fungal pathogens of insects has emphasized the use of these organisms as microbial insecticides. Application of pathogens by inundative release may indeed prove to be a useful tactic, but fungi should not be considered as direct replacements for chemical insecticides. Fungi are complex organisms that interact with their hosts and the environment in intricate ways. Intelligent use of fungi as biological control agents will require detailed knowledge of their pathogenesis, epizootiology and interactions with other components of the ecosystems in which they are to be used. This will become increasingly important as scientists begin to genetically alter fungal pathogens to improve their efficacy as biological control agents.

Some researchers feel that fungus-induced epizootics are too dependent on high host densities and environmental conditions, particularly moisture, to be effective biological control agents (Bucher 1964), however, the majority of researchers who study insect pathogens believe that fungi will play a vital role in IPM systems in the near future (Allen et al. 1978, Carruthers and Soper 1987, Fuxa 1987, McCoy et al. 1988).

Admittedly, fungi are limited in their ability to control insect pests. For example, not all pest species are susceptible to fungal pathogens, and even if susceptible, the target hosts may live in an environment that is not conducive to fungal infection and transmission. As mentioned previously, fungal pathogens are highly dependent on moisture for spore germination and infection. They are also adversely affected by high temperatures. Pest control using any biological control agent will not be as certain or repeatable as the action of chemical insecticides. For this reason, we need to alter our expectations, develop integrated control programs using multiple tactics and continue to improve our efficiency in using fungi and other pathogens as biological control agents. Most importantly, we should develop a research agenda aimed at solving specific problems associated with the development and application of microbial agents for biological control.

Although the list of needed research on fungal pathogens and their use in biological control is long, we would like to highlight five specific areas needing additional attention. First, it is important that fungal pathogen germplasm be collected now and preserved for future evaluation and use. Second, continued expansion of research on fungal epizootiology and ecology is needed so that we may understand disease dynamics, the impact of pathogens on host populations and the factors that limit disease development and spread under field conditions. Third, we need to study genetic aspects of host and pathogen populations that affect the establishment, spread and maintenance of disease in insect populations. We must recognize that natural populations of fungal pathogens contain high levels of genetic variation which could contribute to their ability to regulate host populations. Furthermore, we must explore the potential for the evolution of resistance in the host population before it becomes a problem in the field. Fourth, we must increase our efforts to integrate the use of pathogens with other control tactics. Until control efforts use multiple tactics to manage a complex of pest species IPM will remain in its infancy. Last, we need to expand

the use of innovative techniques in addressing problems associated with biological control agents.

New biotechnologies provide us with tools to address questions that we have never been able to ask before. We expect innovative biological techniques to be used to manipulate desirable traits, and thus improve the effectiveness of some fungal pathogens. Recombinant DNA techniques are being used to study the mechanisms of pathogenicity and virulence at the molecular level. For example, fungal enzymes and associated genes involved in penetration of the insect cuticle have now been identified (St. Leger et al. 1987, 1988a). Knowledge of these genes and gene products may eventually lead to genetic alteration of fungal pathogens. Using transformation systems developed for other types of fungi (Shimazu 1987, Yoder et al. 1987), it may be possible to clone the genes responsible for these products and transfer them to fungi that may have poor penetration ability but are well adapted to a particular environment. The genes involved in toxin production are also candidates for cloning.

Biotechnological methods also are being applied to improve methods for field monitoring of insect fungal diseases. Enzyme linked immunosorbent assay (ELISA) is used to detect a variety of fungi in plant tissues (Mendgen 1986) and has shown promise for detecting fungal cells of *Entomophaga maimaiga* in gypsy-moth larval hemolymph (Hajek et al. 1989). Other techniques such as isoenzyme polymorphisms (Boucias et al. 1982, Micales et al. 1986) and restriction fragment length polymorphisms (RFLP's) will become increasingly useful in detecting different fungal pathogen strains (Hajek et al. 1990).

It is important however, that we do not get lost in the techniques and lose sight of the important question: How can we improve our ability to manage pest problems while improving both our economic and environmental situation? Despite the promise of new technologies, successful biological control depends on a fundamental knowledge of host and pathogen biology, not only at the molecular level, but at the cellular, organismal, population, and ecosystem levels as well. It is evident that specialists from many subdisciplines of entomology, genetics, mycology, systems science and other fields of study will be required to successfully identify, manipulate and use fungi for biological control purposes in the future.

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Use of *Beauveria bassiana* and *Bacillus thuringiensis* for Suppression of the European Corn Borer, *Ostrinia nubilalis*¹

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Abstract

Bacillus thuringiensis and *Beauveria bassiana*, a microbial insecticide, and an entomopathogenic fungus, respectively, are efficacious alternatives to chemical insecticides to suppress *Ostrinia nubilalis*. Past, present, and future of these microbes are presented. *Beauveria bassiana* was first used to suppress *O. nubilalis* on maize in 1934. Early researchers determined the mode of action of *Beauveria bassiana* and utilized this fungus for suppression of *O. nubilalis*. Commercialization of this organism is in its infancy. *B. bassiana* does, however, occur naturally and produces epizootics. Studies initiated to conserve and enhance *B. bassiana* for suppression of *O. nubilalis* led to the discovery of a unique endophytic relationship between *B. bassiana* and the maize plant; this relationship will most likely be exploited in pest management programs. *Bacillus thuringiensis* was utilized in control efforts against *O. nubilalis* as early as 1928. The techniques utilized were primitive, and researchers had little understanding how this bacterium killed *O. nubilalis*. Conceptualized systematic research has been conducted for many years to elucidate the histopathology of this bacterium against *O. nubilalis*, to understand the impact of environmental factors on *B. thuringiensis* and to develop formulations to deliver it to the maize plant to control this serious pest of maize. This research has been the impetus for the commercialization of *B. thuringiensis*. Future management programs will definitely rely greatly on an increased use of these two organisms by themselves, together, and in combination with other entomotoxins.

Introduction

The European corn borer, *Ostrinia nubilalis*, is a primary pest of maize in many parts of the world. It damages maize by feeding on the unfurled leaves in the whorl of the plant during early vegetative stages (whorl stage), by feeding on the leaf sheath tissue of maize during anthesis (pollen-shedding), and, in some instances, by feeding on

the ear. These types of feeding cause economic loss by either direct or by physiological damage (reduction in the nutrient transport systems).

Over the years, many approaches have been taken to suppress damage to the maize plant by *O. nubilalis*. These attempts include all recognized methods; i.e., mechanical, chemical, biological, host plant resistance, and an integration of all methods. In this paper, I will address only a narrow segment within the biological control component, specifically the use of *Bacillus thuringiensis* and *Beauveria bassiana* to suppress *O. nubilalis*.

Bacillus thuringiensis

Bacillus thuringiensis is an aerobic, gram-positive, spore and crystal-forming bacterium with 34 known subspecies categorized into 27 serotypes (de Barjac and Frachon 1990). Many entomotoxins are produced by different subspecies of *B. thuringiensis*; however, delta-endotoxin and beta-exotoxin are toxic to the widest range of insects.

The delta-endotoxin is a crystalline protein produced during sporulation of the bacterium and was first noted by Berliner (1915). The role of the crystal in the entomopathogenicity of this bacterium towards insects was suggested by Hannay (1953) and confirmed by Angus (1954, 1956). Lepidopterous insects, including *O. nubilalis*, vary in their response to the toxin. Growth of *O. nubilalis* larvae is slowed when spores or crystals are fed to the insects (Sutter and Raun 1966), and some mortality occurs when early instars are fed only crystals (Mohd-Salleh and Lewis 1981). The latter researchers, however, reported a substantial increase in mortality of early instars with the addition of spores and found that both spores and crystals were necessary for maximum kill of later instars. *Bacillus thuringiensis* kills *O. nubilalis* by causing a sloughing of the midgut epithelial cells into the gut lumen, exposing the basement membrane to attack by vegetative rods from germinating spores (Sutter and Raun 1967).

The beta exotoxin is a thermostable nucleotide produced at the time of sporulation (Cantwell et al. 1964). It is toxic to several species of insects (de Barjac 1960) including *O. nubilalis* (Mohd-Salleh and Lewis 1982, 1983). It seem-

¹ Joint contribution: USDA, ARS, and the Iowa Agriculture and Home Economics Experiment Station (Journal Paper No. J-14195), Ames, Iowa. Project No. 2513.

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ingly kills insects by inhibiting enzymes involved with nucleotide substrates such as nucleotidases and DNA-dependent RNA polymerases (Sebasta and Horska 1968).

Bacillus thuringiensis is rarely isolated from insects other than in an insectary environment. An extensive survey of microorganisms associated with *O. nubilalis* was made in Iowa; however, *B. thuringiensis* was never isolated (Raun et al. 1959, Raun and Brooks 1963). In a more recent study, *Bacillus thuringiensis* subspecies *kurstaki* was isolated from field-collected egg masses and young larvae of *O. nubilalis* (Lynch et al. 1976a). The bacterium was isolated three times from egg masses and two times from larvae in a total of 221 specimens. These five isolates were pathogenic when tested against laboratory-reared *O. nubilalis* and represents the first report of *B. thuringiensis* isolation from an insect egg (Lynch et al. 1976b).

The use of *B. thuringiensis* to suppress populations of *O. nubilalis* has a long history. Unsuccessful attempts were made to isolate a bacterium from *O. nubilalis* that could be cultured and applied to suppress this pest of maize in Hungary, but researchers did successfully kill *O. nubilalis* larvae with an isolate of *B. thuringiensis* isolated from the mediterranean flour moth, *Anagasta kuhniella* (Husz 1928; Chorine 1929). In other early work in Europe, an isolate of *B. thuringiensis* from *Galleria mellonella* was applied to maize as a spore powder. This preparation killed 90% of the larvae (Metelnikov and Chorine 1929a,b; Metelnikov et al. 1930a,b). In other work, *B. thuringiensis* was applied as a dust or spray, to maize in field experiments suppressing *O. nubilalis* larvae by 96.8 to 99.2%. This work was continued with spray and dust formulations that suppressed *O. nubilalis* up to 2 weeks after application of the bacterium (Chorine 1930). Multiple applications of *B. thuringiensis* 7 days apart also were very effective in reducing plant damage caused by *O. nubilalis* (Husz 1930, 1931).

The aforementioned research with dusts and sprays to apply *B. thuringiensis* involved the unsophisticated combination of the bacterium and a carrier, usually water or talcum powder. The event of commercial production of *B. thuringiensis* triggered widespread efficacy evaluation of this bacterium against many species of lepidopterans. This, in turn, ushered in the era of formulation research with *B. thuringiensis*. Even so, for many years, researchers merely

adopted techniques from the chemical industry to formulate *B. thuringiensis*. These formulations were used in efficacy experiments against *O. nubilalis* in many countries.

In France, granular formulations of *B. thuringiensis* were superior to sprays and equal in some tests to DDT in suppressing damage by *O. nubilalis* (Cangardel and Anglade 1969; Martouret and Anglade 1971). The granular formulations, BactucideG, BactospeineG, and EcatoxG all effectively controlled *O. nubilalis* up to 30 days after application in experiments in Hungary (Injac 1979). An extensive comparison between a *B. thuringiensis* spray, Bactucide P, a granule, Bactucide G, and the chemical Diazinon to suppress *O. nubilalis* were made at many locations in Italy. Granules were always superior to sprays, but neither was as efficacious as Diazinon (Coppolino et al. 1984). In the U.S., attapulgit clay granules, with *B. thuringiensis* adequately suppressed *O. nubilalis* in whorl-stage maize but did not in pollen-shedding maize (Raun 1963). *Bacillus thuringiensis* subspecies *thuringiensis* and *kurstaki* were applied as spray and granule formulations. Granules were superior to spray formulations and equal to DDT and Diazinon in efficacy against *O. nubilalis* larvae (McWhorter et al. 1972). In only one study has a spray formulation been superior to a granular formulation. That was in the Federal Republic of Germany, where a spray formulation of Dipel suppressed *O. nubilalis* by 70%, whereas there was no difference in suppression between the granular plot and the untreated check (Langenbruch 1976).

The previously discussed research was conducted by applying *B. thuringiensis* with over-the-row application equipment. In the west central U.S. corn belt, a large area of maize is grown under irrigation. Researchers attempted to suppress *O. nubilalis* larvae in this area by applying *B. thuringiensis* through center-pivot sprinkler irrigation systems. It was concluded that, even though larval densities were reduced, the magnitude of reduction was too small to recommend *B. thuringiensis* as an economically sound substitute for chemical insecticides (Nolting and Poston 1982).

Occasionally, *B. thuringiensis* is applied to plants other than field maize to suppress larval populations of *O. nubilalis*. When applied to sorghum foliage more than 50% of the original insecticidal activity was lost 24 h after application, making it ineffective (Gardner and Hornby 1987). Likewise, in Israel, Bactospiene III sprayed on

sweet corn leaves lost activity very readily, with no activity remaining 8 days after application (Navon and Melamed-Madjar 1986). In other experiments (Hudon 1962, 1963), a wettable powder of *B. thuringiensis* was applied to sweet corn to control *O. nubilalis*. Efficacy was unsatisfactory compared with recommended chemical insecticides.

It is obvious from many studies that *B. thuringiensis* is efficacious against *O. nubilalis* larvae, but results within and between experiments are highly variable. Research has been conducted to better understand this variability and make *B. thuringiensis* more competitive with chemical products. Also, it was obvious that the placement of *B. thuringiensis* on the plant relative to feeding sites of the larvae and protection of *B. thuringiensis* from the environment were extremely important. Additional work to control maize insects demonstrated the susceptibility of *B. thuringiensis* to degradation from exposure to ultraviolet light (Raun et al. 1966).

The initial work to produce a formulation that would protect *B. thuringiensis* from ultraviolet light involved an encapsulation process (Raun and Jackson 1966). This technique produced a "clump" of bacterial powder surrounded by a capsular wall. The powder was then prepared as a spray, a granule, or an emulsifiable concentrate and applied to maize. These formulations were effective in suppressing larval populations of *O. nubilalis*; reduction ranged from 45% with sprays to 90% with granules compared with untreated checks. DDT granules (5%) reduced larval populations by 90% also. More recently, granule volume and concentration of pathogen in the granules were evaluated. Clay granules differing in thuricide HPC concentration (5.6, 11.3, and 22.5% wt./wt.) were applied to maize during the whorl- and pollen-shedding stages of plant development. Granule volume per unit area did not significantly influence the degree of control, but the 22.5% concentration was significantly more effective than the 11.3% concentration (Lynch et al. 1977b). In a continued effort to understand the lack of consistency with which *O. nubilalis* larvae can be suppressed, two granular formulated products, Dipel and Thuricide HPC, were applied to maize on an equal basis; i.e., equal number of international units. This approach reduced variability between commercial products (Lynch et al. 1977a).

Efficacy of *B. thuringiensis* is routinely measured by counting the number of larvae remaining in a plant or by

measuring physical damage to the maize plant caused by *O. nubilalis*. In an attempt to delineate additional factors other than the environment that produce variability in efficacy of *B. thuringiensis*, products research was conducted to quantify the amount of *B. thuringiensis* deposited in the target area of the plant and the persistence of this material when applied with granular, foam, or spray formulations.

These researchers (Lynch et al. 1980) found that granular and foam formulations applied to maize were more effective than a spray formulation. Also the granular and foam formulations were superior to the target-area deposits. *Bacillus thuringiensis* applied with these formulations persisted longer than that delivered by a spray formulation. The latter work again indicated that, when *B. thuringiensis* is placed where *O. nubilalis* feeds in the plant (i.e., within the whorl or behind the leaf-sheath collar) its efficacy is greatly increased. This was instrumental in initiating research to develop a granule formulation that would both deliver *B. thuringiensis* to the target area and protect it from ultraviolet (UV) light.

A simple and potentially economically feasible macroencapsulation system involving the use of starch to encapsulate *B. thuringiensis* was developed (Dunkle and Shasha 1988). This unique system allows for the easy addition of phagostimulants, feeding attractants, and UV protectants such as congo red. The addition of congo red greatly extended the life of *B. thuringiensis*. More than 50% of the original spore activity remained 12 d after exposure to unobstructed sunlight in a plastic arena (Dunkle and Shasha 1989). Granules made with the starch-matrix process have been evaluated for *O. nubilalis* suppression in the field. The UV screen, congo red, and a feeding stimulant, Coax, were used as additives. Congo red did not increase efficacy of *B. thuringiensis*; however, when Coax was added to the smallest dosage of *B. thuringiensis*, larval suppression was equal to that from the treatment that contained four times as much *B. thuringiensis* (McGuire et al., in press). Research with starch encapsulation is continuing and will most likely add greatly to the effort to make *B. thuringiensis* an economical as well as efficacious alternative to chemical insecticides.

The future of *B. thuringiensis* for suppression of *O. nubilalis* is very promising. The public is demanding and many producers, especially hybrid maize seed producers, are looking for alternatives to chemical insecticides. The starch matrix granule has shown great promise as a superior

delivery system for this bacterium. Furthermore, genetic engineering has been utilized to develop new *B. thuringiensis* products specifically for suppressing *O. nubilalis*. Genes for toxin production in *B. thuringiensis* are carried on plasmids. These plasmids can be taken from *B. thuringiensis* isolates and inserted into another (Carlton 1988). This technique has been used to develop Foil, a *B. thuringiensis* product with both coleopteran and lepidopteran activity to control *O. nubilalis* and *Leptinotarsa decemlineata* on potatoes. MCap was developed by using recombinant DNA techniques in which the gene that produces *B. thuringiensis* toxin was inserted into *Pseudomonas fluorescens*, also a naturally occurring bacterium. The *P. fluorescens* carrying the *B. thuringiensis* toxin gene are then killed, forming a biocapsule around the protein crystal protecting it from harsh environmental factors. Little experimentation has been reported in which efforts have been made to develop transgenic plants specifically for use against *O. nubilalis*. The possibility for success is unlimited. Investigations are under way to introduce the toxin of *B. thuringiensis* into maize by incorporating the gene controlling toxin production into an endophytic bacterium (*Clavibacter xyli* subsp. *cynodontis*). This transgenic bacterial endophyte (InCide) is forced into the maize seed, resulting in a plant containing *B. thuringiensis* toxin. Presently, toxin production within the plant is insufficient to kill insects. The development of transgenic plants or the use of transgenic endophytes does, however, create a dilemma. The problem is the development in *O. nubilalis* of resistance to *B. thuringiensis*. Resistance was not considered a possibility until the discovery of resistance to *B. thuringiensis* in *Plodia interpunctella* (McGaughey 1985). We, as crop protection specialists, must be cognizant of this possibility and develop methodologies to manage resistance and, in turn, maximize the products of maize research.

Beauveria bassiana

Beauveria bassiana is an ubiquitous entomopathogenic fungus efficacious to many species of insects, including *O. nubilalis*. *Beauveria bassiana* is readily isolated from the soil and plant debris of a maize agroecosystem, and it can cause an epizootic in *O. nubilalis* on a yearly basis (Lewis 1985). *Beauveria bassiana* kills insects when a conidium attaches to larval epicuticle, germinates, penetrates the cuticle, develops hyphal bodies, and produces toxic

metabolites (Lefebvre 1934; Roberts 1981). The specific histopathology of *B. bassiana* invasion of *O. nubilalis* has been described (Lefebvre 1934).

Earlier work with *B. bassiana* for maize plant protection was similar to that with *B. thuringiensis* in technique. Conidia were combined with cornstarch or wheat flour and dusted on plants. Larval mortality of 1 to 79% was obtained (Bartlett and Lefebvre 1934). Other workers applied conidia in a flour carrier at 11-d intervals to pollen-shedding maize and reduced the *O. nubilalis* by 33 to 63% (Stirret et al. 1937). These researchers reported the importance of placement of *B. bassiana* on the plant, timing of application relative to insect infestation, and microhabitat. They also reported that plant damage occurred before the larvae were killed; e.g., there was a 60-70% reduction in larval population but little reduction in plant damage (Beall et al. 1939).

Little additional data were reported on the use of *B. bassiana* for *O. nubilalis* suppression for 20 years. In a renewed effort, sprays, dusts, and granulars were utilized to deliver *B. bassiana* to whorl-stage maize. More than over 90% of the larvae were killed; however, these formulations of *B. bassiana* were ineffective against *O. nubilalis* on mature maize (York 1958). Over 95% reduction of *O. nubilalis* larvae has been reported in the People's Republic of China by applying 1.5×10^8 conidia per plant (Hsiu et al. 1973), and larval populations were reduced by 91.1% in France with 1×10^{12} conidia per ha (Riba 1984). Dosage of conidia, isolate of the fungus, and stage of *O. nubilalis* larvae are very important when attempting to maximize the response to *B. bassiana*. First instars are reported to be most susceptible (Feng et al. 1985). Also fourth instars are the least susceptible. Isolates of *B. bassiana*, however, differed greatly in pathogenicity (Feng et al. 1985).

In efforts to better understand the high variability and many times low efficacy of *B. bassiana* against *O. nubilalis*, recent research has defined the microhabitat necessary for this fungus to express its pathogenic properties. Temperature is the dominant factor affecting *in vivo* mycoses in *O. nubilalis* (Carruthers et al. 1985). Relative humidity (RH) is very important, not only for survival of the fungus, but also for invasion. Conidia of *B. bassiana* can invade the cuticle of *O. nubilalis* at 30% or 70% RH; however, the lethal time was increased at the lower RH (Riba and Marcandier 1984). *Beauveria bassiana* is readily found in nature in the soil, on decaying organic material, and on

insect cadavers and insect eggs (Raun et al. 1959; Brooks and Raun 1965; Lynch and Lewis 1978; McCoy et al. 1988). This fungus is readily isolated from field-collected larvae. *Ostrinia nubilalis* collected for laboratory colonization must be surface-sterilized *B. bassiana* conidia (Lewis, unpubl. results). Diapausing *O. nubilalis* larvae have been collected from several locations in France and later died from *B. bassiana* infection within 60 d (Marcandier and Riba 1986).

Research has been conducted recently to better understand the temporal relationships between *B. bassiana* and *O. nubilalis* within a maize ecosystem. Researchers developed a model predicting the timing of larval mortality following exposure to *B. bassiana* (Feng et al. 1988). When *B. bassiana* conidia and *O. nubilalis* larvae were placed on the plant simultaneously, more than 60% of the larvae were killed. When conidial application preceded larval application, mortality decreased linearly as the time between applications increased. These researchers concluded that maximum mortality occurs when *O. nubilalis* larvae and conidia come in contact immediately. Anything delaying this meeting decreases mortality. Possible explanations are that larvae move to inner areas of the plant and do not readily contact the fungus or that the fungus precedes arrival of the larvae, and viability of the conidia is lost.

In a different, but related, temporal experiment, larvae and conidia were applied to whorl-stage maize, and 3 d later, *B. bassiana* conidia were applied. Mortality in excess of 70% was recorded (Lewis and Cossentine 1986). This experimentation was continued by infesting these plants in the pollen-shedding stage with additional *O. nubilalis* larvae. Tunneling by the latter larvae was significantly reduced by *B. bassiana* placed on the plant 4 weeks earlier. Researchers hypothesized that conidia were produced from insect cadavers from the first larval infestation or that conidia from the original inoculum remained viable on the plant. Recent work has suggested another explanation for this extended conidial viability. *Beauveria bassiana* was applied to whorl-stage maize by using a granular formulation (Lewis and Bing, in press). This inoculum caused a significant reduction of larvae during this stage and also significantly reduced larvae from the filial generation of *O. nubilalis*. This reduction in larval damage was significantly correlated with the incidence of *B. bassiana* in the pith of the plant.

Beauveria bassiana is known to colonize certain genotypes of maize (Vakili 1990). It has been isolated from the pith of several inbred lines. It is now evident that the season-long suppression of *O. nubilalis* larvae reported by Lewis and Cossentine (1986) and Lewis and Bing (submitted) was probably due to colonization of the maize plant by *B. bassiana*. A hybrid maize was utilized in both of these studies; thus, the phenomenon is not unique to inbred maize lines.

Evidence is very strong that an endophytic relationship exists between *B. bassiana* and the maize. Subsequent research confirms this and provides additional insight into this phenomenon (Bing 1990). *Beauveria bassiana* was applied to whorl-stage maize plants by a granular formulation or injected into the plant above the growing tip by using a medical syringe and hypodermic needle. Pith samples were removed from plants at senescence and assayed for *B. bassiana*. The fungus persisted in the pith of the plants and significantly suppressed *O. nubilalis* larvae throughout the season. In additional studies, *B. bassiana* was again applied by granular formulation or injection to whorl-stage maize. *O. nubilalis* larvae were then placed on the plants at whorl stage, late-whorl stage, and pretassel stage of plant development. At senescence, suppression of *O. nubilalis* was determined by measuring larval tunneling. Larvae applied at the two earlier stages of plant development caused significantly more tunneling than those applied at pretassel stage of development. Most likely, this reduction was due to *B. bassiana* colonizing more of the plant by the late developmental stage. In a final study in which plants were injected with *B. bassiana* at anthesis, it was determined that the inoculum moved upward in the plant perhaps with plant photosynthesis. Furthermore the presence or absence of *O. nubilalis* larvae did not influence the endophytic relationship between the fungus and the plant.

Combinations of Entomotoxins

Reports of the simultaneous use of more than one microbe to suppress populations of *O. nubilalis* are infrequent. Theoretically, two pathogenic organisms would stress the insect and increase the efficacy of each. Extensive research was conducted in which *O. nubilalis* larvae were placed on whorl-stage and pollen-shedding-stage plants. Subsequently, these plants were sprayed with a suspension of *Nosema pyrausta*, a microsporidium. Then a granular

formulation of *B. thuringiensis* was applied to the same plants. *B. thuringiensis* and *N. pyrausta* were additive in terms of reducing larval populations (Lublinkhof et al. 1979). In a similar study in which the larvae were transovarially infected with *N. pyrausta*, *B. thuringiensis*, and *N. pyrausta* acted independently in suppressing the larvae (Lewis et al. 1982). There were, however, several interactions indicating a more severe impact from *N. pyrausta* in a transovarial infection than that from a per os infection.

In additional research using a split-plot experimental design, (Lewis, unpublished) *B. thuringiensis* and Furadan, a carbamate insecticide, were combined with *B. bassiana* to suppress *O. nubilalis* larvae. *B. bassiana* alone and in combination with the microbial and chemical insecticides significantly reduced damage by *O. nubilalis* larvae. There were no significant interactions between whole-plot and split-plot treatments. In a study to provide immediate and season-long suppression of *O. nubilalis*, *B. thuringiensis* and *B. bassiana* were formulated on granules and applied separately and in combination to field maize. Each pathogen and combination of pathogens caused a significant reduction in tunnelling compared with the check. *Beauveria thuringiensis* and *B. bassiana* were independent of each other in their impact on insect suppression (Lewis and Bing, submitted).

The impact of two indigenous insect pathogens, *B. bassiana* and *N. pyrausta*, in suppressing *O. nubilalis* was investigated. *B. bassiana* alone reduced larval damage by 63% compared with that of the check; *N. pyrausta* alone reduced larval damage by 68%, and the combination of pathogens reduced plant damage by 78% (Lewis, unpublished data).

In general the efficacy of *Bacillus thuringiensis* and *Beauveria bassiana* against *O. nubilalis* is not compromised when either is applied to maize in combination with another toxicant. The response is usually independent and often additive. Future research should build on these data in developing ecologically sound management systems for *O. nubilalis*.

Acknowledgment

The author acknowledges Lori Anderson Bing and John J. Obrycki for their critical review of this manuscript.

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The Development of the National Biological Control Institute

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Abstract

A National Biological Control Institute has been established by the United States Department of Agriculture, Animal and Plant Health Inspection Service in Hyattsville, Maryland. Its mission is to promote, facilitate and expedite biological control and provide national leadership.

Introduction

The United States Department of Agriculture (USDA), in addition to other national and international agencies, is vitally concerned about the misuse of pesticides. A shift in emphasis toward non-chemical pest control techniques is being implemented by a multitude of federal agencies. This can directly benefit the farmers in terms of increased safety and reduced production costs in comparison to use of dangerous and expensive pesticides. There is growing support in Congress for information and support for projects emphasizing non-chemical approaches to combat such pests as grasshoppers, wheat aphids, hydrilla, leafy spurge, and others. Biological control is an effective non-chemical technology now available for the control of a wide variety of agricultural pests.

Justification for Biological Control

The justification for biological control technology is to assure food safety and affordability, enhance water quality, prevent disease transmission, replace obsolete pesticides, protect biodiversity, reduce petroleum depletion, and increase profitability of farming. In addition, it protects endangered species, and overcomes pesticide resistance in target pests.

Definition of Biological Control

The definition of biological control adopted for this presentation is "the action of parasites, predators or pathogens in maintaining another organism's population density at a lower average than would occur in their absence" (DeBach 1964).

Historical Accounts

Through the "cooperation" of numerous research institutions such as the USDA, Agricultural Research Service (ARS), Cooperative State Research Service (CSRS), Extension Service (ES), and operational agencies such as state departments of agriculture and the USDA, Animal and Plant Health Inspection Service (APHIS), many classical biological control programs have been completely successful in the United States. The cottony cushion scale, *Icerya purchasi* Maskell, was found attacking citrus in California as early as 1868, but was successfully controlled in 1889 by the vedalia beetle, *Rodolia cardinalis* (Mulsant) (Doutt 1958). Other complete successes include the cereal leaf beetle, *Oulema melanopus* (Linnaeus), which was attacking oat, wheat and barley (Pierce 1982); the citrus blackfly, *Aleurocanthus woglumi* Ashby, attacking citrus (Dowell et al. 1979); the Comstock mealybug, *Pseudococcus comstocki* (Kuwana), attacking citrus and ornamentals (Meyerdirk et al. 1981); and the alfalfa weevil, *Hypera postica* (Gyllenhal) on alfalfa (Day 1981).

USDA, APHIS Biological Control Operational Programs

APHIS has established two strategic biological control operational laboratories within the agency. One is located at Niles, Michigan and the other at Mission, Texas. A satellite laboratory facility also has been established in Bozeman, Montana to accommodate the biological control of weeds programs. Operational programs are being conducted against the alfalfa weevil, Russian wheat aphid, *Diuraphis noxia* (Mordvilko), the Colorado potato beetle, *Leptinotarsa decemlineata* (Say), the European corn borer, *Ostrinia nubilalis* (Hübner), diffuse and spotted knap-weeds, *Centaurea diffusa* Lam. and *C. maculosa* Lam., and leafy spurge, *Euphorbia esula* Linnaeus.

As an action Agency, APHIS plans to develop a greater commitment to enhance our biological control activities within the United States.

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National Biological Control Institute

APHIS has recently established the National Biological Control Institute (NBCI) to serve as a focal point for providing national leadership in coordinating and implementing the regional and national use of natural enemies in suppressing agricultural pests. NBCI will serve as a national resource for the collection, analysis, and dissemination of general information and scientific findings regarding biological control.

Reason for Establishment by USDA, APHIS

The reason for the establishment of the NBCI by USDA, APHIS was to assure success in the development and implementation of biological control programs. There was a need for an action agency at the national level to provide leadership in the implementation of regional or national programs for biological control of agricultural pests. State and local governments are not in a position to support such efforts. The increased commitment by APHIS to applied biological control fills a void not formerly supported by industry. As a result of the establishment of the NBCI, the implementation of biological control in the United States will be able to excel to its maximum potential.

Mission

The mission of the NBCI is to promote, facilitate, and expedite biological control and provide national leadership. The NBCI will serve as a national resource for the collection, analysis and dissemination of biological control data, provide training and technical information, service State cooperators, and assist APHIS and other Federal Agencies in expediting state, regional or national biological control programs. The Institute will enlist involvement of research institutions, identify and support the needs of cooperators and other interest groups, facilitate and coordinate technical education and training in biological control, and interface with other integrated pest management technologies.

Linkage to Other Organizations

Research, development and implementation efforts in biological control involves collective support from federal and state agencies, universities, and the private sector. An

improved communication process is being developed to assure close cooperation between APHIS, ARS, CSRS and other federal agencies, plus state cooperators including universities, agricultural experiment stations and departments of agriculture, plus the private sector including industry, special interest groups and other cooperators. Biological Control Working Groups already established in ARS include: classical, augmentation and conservation, microbial, ecology and behavior, and natural products. A USDA Interagency Biological Control Coordinating Committee (IBC³) also has been developed within USDA. The NBCI will develop close linkages with these groups and others. In addition, the NBCI will develop a management team and establish a User-Advisory Committee comprised of a variety of Federal agencies which will advise, identify and prioritize national biological control programs within NBCI.

Location

The NBCI is located in the Federal Building on the fifth floor in Hyattsville, Maryland and houses the Information and Documentation Center and administrative staff.

Organization

The NBCI organization consists basically of a Director, Technical Consultant, Database Manager and Technical Coordinator.

Director

The director will provide active and supportive leadership for the NBCI. He or she will manage the institute's resources, establish a user-advisory committee, develop initiatives, develop strategic and operational plans; implement marketing programs, maintain financial support, and assure the quality of all services performed by the NBCI.

Technical coordinator

The technical coordinator will foster APHIS and interagency liaison, integrate biologically based technologies, coordinate biological control method development needs, communicate and publicize biological control, monitor APHIS extramural projects, facilitate training and implementation, and build a biological control network.

Technical consultant

The technical consultant will provide technical advice to a variety of user groups, provide technical information, build informational linkages, and will also be responsible for communicating and publicizing biological control.

Database manager

The database manager will supervise the Documentation Center, develop and maintains all databases, develop and maintain computer programs; and provide reports for specific applications. Data will include tracking all foreign collection information, importation, quarantine screening, release and establishment of exotic natural enemies.

Organizational Interface Within APHIS

APHIS is comprised of several units under the Administrator including Plant Protection and Quarantine (PPQ). The biological control operational program and laboratories are in PPQ. The NBCI will provide a strong linkage and support of PPQ operational programs to the Methods Development Centers within APHIS and other Federal Agencies.

Conclusion

Never before in the history of organized agriculture has there been a period when so much interest and need for biological control could be coupled with the technology for its implementation. Biological control has moved to the forefront as a viable means of controlling animal and plant pests. We now have the opportunity to develop and implement biological control programs that will significantly improve food safety and affordability, prevent transmission of animal and plant diseases, provide alternative pest control technologies, protect biodiversity, enhance water quality, and preserve the overall environment. The NBCI will enhance our opportunities of developing sound biological control programs in the United States and potentially international programs.

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